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GROUP TECHNOLOGY APPLICATIONS IN SHIPBOARD PIPING SYSTEM MANUFACTURE

by

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Submitted to the Department of Ocean Engineering in partial fulfillment of the requirements for the degrees of Ocean Engineer and Master of Science in Mechanical Engineering.

ABSTRACT

Shipbuilding in the United States is examined in the context of its productivity problem and the possible solutions offered by modern shipbuilding techniques. Specifically, group technology is applied to naval shipboard piping systems. A nine digit code is developed to identify pipe assembly manufacturing attributes, with emphasis placed on utilization of the code for workload balancing and reduction of setup time. Use of the code for rudimentary shop routing is also discussed.

The code is shown to serve as an excellent means of organizing pipe assembly information into a usable data base. FFG-7 pipe assembly statistics are used as the basis for a quantitative analysis of pipe shop work processes. Incomplete data limits the ability to conduct accurate workload balancing forecasts at the present time. Use of the coding scheme would help to fill that gap because of its inherent work content estimating capability; however, additional data is also needed in order to develop a more accurate manhour requirement algorithm.

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First and foremost, I would like to express my deepest gratitude to Dr. Daniel Whitney for his excellent support and guidance on this project throughout the past year.

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CHAPTER 1

SHIPBUILDING IN THE U.S. TODAY

1.1 Overview

Phrases such as "flexible automation" and "factory of the future" pervade the vocabulary of those seeking to boost future industrial productivity. Indeed, factory automation is a powerful tool for achieving higher productivity, and its rapid growth is unmistakably one of the predominant trends of this and future decades. Shipbuilding, however, has been slow to jump on the automation bandwagon. Low quantity production and high unit cost make ships less than an ideal target for the application of robotics technology. Nevertheless, a strong desire to reduce shipbuilding costs is forcing the industry to examine methods of implementing the automation technology that has been so successful in other industries. The quest for automation, however, must be preceded by a quest for innovation--innovation in the basic industrial process by which ships are built. After shipbuilding work has been restructured into its most logical and efficient organization, then it is appropriate to see how that work might be automated.

This thesis attempts to take a comprehensive look at shipbuilding in the United States today, then focuses on the subject of innovation of the industrial process, with piping system fabrication receiving a detailed analysis. The objective will be to improve piping fabrication productivity through the application of modern industrial engineering principles, particularly group technology. The remainder of this chapter is devoted to overviewing the problems in the U.S. shipbuilding industry today. Chapter 2 discusses methods used to increase productivity in

World War II. Chapter 3 outlines the naval ship design process and delineates the various costs involved in naval ship acquisition. Modern industrial engineering techniques and their applications to shipbuilding are covered in Chapter 4. Chapter 5 focuses on piping systems and details the industrial processes involved in piping system fabrication. Chapter 6 looks specifically at applying group technology to pipe fabrication through the design of a coding and classification scheme. The practical use of this code in a shipyard pipe shop is the subject of Chapter 7. Finally, a summary and conclusion are given in Chapter 8.

1.2 Introduction

Shipbuilding in the U.S. today is among the least competitive of this country's international industries. It is a business plagued by low market share, high prices, schedule delays, and unsteady demand. It is indeed an unfortunate situation for an industry which, forty years ago, had amazed the world with wartime shipbuilding achievements that few had thought possible. These achievements will receive detailed scrutiny in Chapter 2; the intent of this chapter is to briefly trace the degradation of the U.S. position in the world shipbuilding market, to overview the present state of affairs in U.S. shipbulding, and to describe the nature of the current U.S. shipbuilding problem.

1.3 Shipbuilding Since World War II

Following World War II, Daniel Ludwig, owner of National Bulk Carriers, desired to build very large iron-ore carriers for the U.S.-Venezuela trade.(1) Since his company's yard in Norfolk, Virginia (Welding Shipyards), was too small, he sought to buy an existing facility elsewhere that could handle the task. Elmer Hann, who came to work for NBC after managing the Swan Island shipyard for Henry Kaiser during the war, led the search and eventually decided on the Kure Naval Shipyard in Japan. The yard had a 150,000 dwt capacity dry dock with good cranes,

and the Japanese were completely willing to lease portions of the facilities. A ten-year lease was signed in 1951, marking the beginning of the Japanese revolution in shipbuilding. Japan's industries were struggling to get back on their feet, so its scientists, engineers, and industrialists were eager to learn everything they could from any available source. The Kure Shipyard lease specifically required that NBC's activities remain open to interested Japanese engineers, over 4000 of whom ended up visiting the yard during the course of the lease.

> Elmer Hann taught the Japanese organization of work in accordance with the basic principles of Group Technology, emphasis on welding without distortion to control costs, the importance of college-educated middle managers trained in the entire shipbuilding system, etc. With such methods and only pre-World War II shipyards, by 1964 Japanese yards were producing 40% of the world's total shipbuilding tonnage.(2)

Concurrently with Elmer Hann's work, the Japanese became intensely interested in the statistical control work of Dr. W. Edwards Deming. Dr. Hisashi Shinto, Chief Engineer under Elmer Hann (and later president of Ishikawajima-Harima Heavy Industries Co.), was the key figure in applying statistical control methods to Japanese shipbuilding. The results were so dramatic that the Japanese society of Naval Architects reported in 1967 that statistical control "laid the foundation of modern ship-construction methods and made it possible to extensively develop automated and specialized welding."(3)

No such revolution was occurring in the United States during the same time period. By 1962, the U.S. share of world shipbuilding was only 4.9% of the gross registered tonnage.(4) The situation was worsened by the slowed growth of productivity in the 1960's. For U.S. industry as a whole, productivity was growing at only 3.1% annually by the mid-1960's, compared to 11% in Japan and 5 to 6% in Western Europe. By the end of the decade, output per manhour in the U.S. was growing at only 1.7 percent per year, much less than the growth rate of wages.(5) Since shipbuilding is labor intensive, this productivity-wage gap had a devastating impact. By 1973, the U.S. ranked tenth in merchant ships under

construction and on order, with only 2.6% of the world total.[6] The 1973 selling price of an 86,000 deadweight ton tanker was about $30 million for a U.S. built ship, compared to about $18.5 million for one built in Japan. Northern European shipyards were also utilizing advanced construction techniques, and the price of an equivalent ship built in Sweden was about $20 million.[7] U.S. companies began to improve their techniques and facilities in the 1970's, but these improvements have only recently produced measurable results. Consequently, U.S. shipbuilding competitiveness continued to decline through the rest of the 1970's. John Arado, Vice President of Chevron Shipping Company, stated in 1983:

> In our latest survey of prices around the world, U.S. prices for tankers were 90% higher than in Europe and 2 to 3 times higher than in the Far East. ... the delivery situation in the U.S. seems, if anything, to be worsening. Unfortunately, long and delayed deliveries in U.S. yards appear to be a way of life.[8]

1.4 The Productivity Problem

Higher wages are frequently blamed for the high cost of U.S. built ships, but low productivity is the real source of the problem. A&P Appledore Limited compared several U.S. yards with four comparably sized foreign yards building merchant ships and concluded in 1980 that "productivity in the best Japanese and Scandinavian yards is on the order of 100% better than in major U.S. shipyards."[9] A major U.S. tanker owner compared labor costs for 1983 ship deliveries in the U.S., Japan, and Europe. While wage rates were slightly lower in both Japan and Europe, direct labor hours were significantly lower. Japan required only 46% of the U.S. direct labor hours to build a similar ship, and the European yard required only 57% of the hours. Material costs were also lower (70% and 78%). An even more detailed study was done by the Levingston Shipbuilding Company in 1980. The study compared labor hours and material costs at IHI with those at Levingston for construction of a modified IHI designed bulk carrier. The results, shown in Table 1.1, reveal that IHI was able to construct a similar ship with only 27% of the labor hours and 65% of the material costs of the U.S. yard.

Table 1.1 Ratio of IHI to Levingston labor hours and material costs.(10)

Item	Labor Hours	Material Costs
Preliminary and staff items	0.24	0.54
Hull steel items	0.22	0.78
Minor steel items	0.42	0.58
Machinery items	0.47	0.66
Outfitting items	0.35	0.56
ALL ITEMS	0.27	0.65

There are many possible reasons to explain why U.S. shipbuilding technology fell so far behind--sporadic demand, a weak supplier base, poorly designed subsidies, over restrictive standards and regulations, cultural factors, etc. While a thorough analysis of each of these issues is beyond the scope of this thesis, there are several which must be addressed. The fundamental difference between good and poor shipyards is the organization and control of shipbuilding work. It is not high-tech facilities or quantity production (although these certainly can be factors). The maximum difference in total construction cost between pre-World War II Japanese shipyards which have been modernized and the newest shipyards which incorporate extensive automation is roughly 12%.(11) This difference, while significant, is but a fraction of the cost differential between Japanese and U.S. yards. Quantity production will be discussed in detail in Chapter 2, when it will be estimated that it increased World War II efficiency by 100%. Nevertheless, a well organized shipyard can overcome many of the inherent inefficiencies of small quantity production. IHI of Japan, for example, is extremely productive in spite of the fact that in 1982 it "delivered 16 ships, no two identical, to 15 owners in 11 countries," while also producing complex naval ships and a polyethylene plant.(12) There is no doubt that it could have been even more productive producing 16 identical ships, but that is just an added benefit from the learning curve; it would be in addition to the more fundamental advantage that is derived from restructuring the

work so as to achieve a well organized and controlled industrial process. Such reorganization is just beginning to achieve significant results in the U.S. and will be discussed in more detail in Chapter 4.

1.5 Naval Shipbuilding

All the discussion so far has been on merchant ships, yet the majority of shipbuilding in the U.S. is and will continue to be naval ships. Not only would it be difficult for merchant shipbuilders to recapture a significant market share from the Japanese and Northern Europeans, but it will also be very difficult to compete with Far Eastern countries such as Taiwan and China, which are now entering the shipbuilding industry. The extremely low wages earned in these countries gives them a significant advantage over even the most efficient foreign firms. Naval shipbuilding, on the other hand, will always be done in the U.S. for security and strategic reasons. There are currently 17 privately owned U.S. shipyards actively engaged in naval shipbuilding with a projected 5 year total value of $88.8 billion. These yards are listed in Table 1.2 along with the most complex type of ship each yard produces. Some of the noncombatant yards are in the process of moving toward combatant ship construction, and there are 7 additional private yards either engaged in naval ship conversion or actively seeking navy contracts.

Shipbuilders do not compete in the world market with their naval products in the same manner that they do with their merchant products. Furthermore, naval ship design is more specialized to suit each country's needs; accurate comparison of naval shipbuilding productivity is therefore more difficult. The limited comparisons that have been made, however, do not show the same schedule and cost gap between U.S. and foreign shipyards that characterizes merchant shipbuilding.(13) This could either mean that U.S. yards do a comparatively better job with naval ships, possibly because of more steady demand, or that foreign yards have not yet solved the more difficult problem of applying modern shipbuilding techniques to complex warships. The real answer probably lies somewhere

Table 1.2. Shipyards currently involved in naval ship construction.[14]

	Combatant			
	Nuclear ($34 billion)	Non-Nuclear ($30 billion)	Noncombatant ($24 billion)	Coastal ($0.8 billion)
GD - Electric Boat	*			
Newport News	*			
Bath Iron Works†		*		
Ingalls		*		
Todd†		*		
American			*	
Avondale†			*	
Beth-Sparrows Point			*	
GD-Quincy			*	
Lockheed†			*	
NASSCO†			*	
Penn Ship			*	
Tacoma			*	
Bell Halter				*
Derektor				*
Marinette				*
Peterson				*

† Currently employing Japanese consultants[15]

in the middle. This thesis will include discussion of both naval and merchant shipbuilding--most of the experience is with merchant ships, but the future applications are intended for naval ships.

CHAPTER 2

SHIPBUILDING IN WORLD WAR II

2.1 Introduction

Any comprehensive examination of shipbuilding productivity must include a look at the ship production methods used in World War II.[16] The speed with which ships were built during the war was staggering. Between 1939 and 1945, a total of 5777 ships were delivered in the U.S. Maritime Commission program. In monetary terms, these ships represented over $13 billion in contracts. Naval ships, although only one-fourth the number, (17) represented an even greater financial investment, totalling over $18 billion (exclusive of ordnance costs). This chapter, however, will deal exclusively with the ships which fell under the jurisdiction of the Maritime Commission. These included some military-type vessels, such as armed transport ships, but were primarily cargo ships and tankers. The principles which will be discussed in later chapters are better demonstrated by the merchant shipbuilding program, and data on merchant shipbuilding was much more readily available.

2.2 Pre-War Shipbuilding in the U.S.

Following World War I, U.S. shipbuilding sank into a deep recession. This slump continued in merchant shipbuilding until passage of the Merchant Marine Act of 1936, which established the U.S. Maritime Commission and empowered it to use subsidies to stimulate merchant ship construction. At the time, there were only 7 companies in the U.S. building

ocean-going ships. These companies and their respective shipyards are listed in Table 2.1. A number of other companies, most notably the Todd Shipyards Corporation, were involved in ship repair.

Table 2.1. Shipyards prior to World War II.(18)

Company	Shipyard	Remarks
Newport News SB & DD	Newport News, VI	
Federal SB & DD	Kearney, NJ	Owned by U.S. Steel
New York SB	Camden, NJ	
Sun SB & DD	Chester, PA	Owned by Sun Oil
Bethlehem Steel	Fore River, MA Staten Island, NY Sparrows Point, MD San Francisco, CA	
Electric Boat	Groton, CT	Submarines only
Bath Iron Works	Bath, ME	Destroyers only

(SB = Shipbuilding, DD = Dry Dock)

The Maritime Commission, under the direction of RADM Emory S. Land (later VADM), aggressively pursued its goal of rebuilding the U.S. merchant marine. It became deeply involved in every phase of shipbuilding, from ship design to contract award to facilities development. In 1938 it enacted its "long range program," which called for the construction of 50 ships per year for 10 years. These ships were to be of a design which came to be known as "standard-types," thereby distinguishing them from emergency, military, and minor-types of ships. Standard dry cargo carriers were designated C-types and were further categorized as C1, C2, or C3, depending on displacement. The major design characteristics of these are listed in Table 2.2.

The Merchant Marine Act of 1936 had given the Navy a voice in merchant ship design, since there was the possibility that merchants might

Table 2.2. Standard cargo ships.[19]

Ship type	Displacement (tons)	Length (ft)	Speed (kts)
C1	2400	418	14.0
C2	4500	460	15.5
C3	5400	492	16.5

need to be quickly converted to military use in time of war. Standard-type ships reflected this influence primarily through their higher speeds. Previous designs had used reciprocating engines and had top speeds of around 11 knots. Standard-types used high speed turbines with double reduction gears (a fairly new technology at that time), thereby allowing both the turbines and the propeller to turn at their most efficient speeds. The result was faster ships with record fuel economy. The C3's also incorporated high temperature, high pressure steam plants, which actually enabled some of them to exceed their design speed by as much as 3 knots.

Another significant feature of the C-types was standardization of design. Previously, each merchant ship had been custom built for the particular route it was to be used on. In designing the C-types, the Maritime Commission consulted with the operating companies and came up with 3 designs of varying displacement that were fairly flexible in their end use possibilities. Minor modifications could then be made after construction. The Maritime Commission also changed from single ship contracts to contracting for 4 to 6 identical ships at one time. These changes were made with the explicit purpose of facilitating the implementation of mass production techniques in shipbuilding.

2.3 Shipbuilding Expansion

The outbreak and growth of war in Europe in 1939 and 1940 made it necessary that the U.S. accelerate its shipbuilding schedule, both to support European allies and to prepare for possible U.S. involvement. In January 1941, the U.S. embarked on the first of what historians now refer

to as the five waves of expansion of ship production goals. The first wave called for 60 ships to be delivered to the British, and 200 more to be built for U.S. use. Since the turbines and reduction gears used in standard-types were in short supply and could not support such an ambitious building program, a simpler design was decided on. These "emergency ships," which later came to be known as Liberty ships, were to have reciprocating engines with low pressure boilers and a top speed of only 11 knots. The second and third waves occurred later in 1941, then the fourth and fifth waves occurred in the first few months following the attack on Pearl Harbor. Production goals came to be set in deadweight tons rather than number of ships, since the critical need was for cargo-carrying capacity. By the end of February 1942, following the fifth wave, U.S. merchant shipbuilding goals stood at 9 million deadweight tons in 1942 and 15 million deadweight tons in 1943. Each Liberty ship was about 11,000 deadweight tons. Despite serious doubts as to whether these goals could be achieved, the 2-year total was, in fact, exceeded by more than 3 million tons (although 1942 fell slightly short). Figure 2-1 shows the deadweight tons actually produced in the Maritime Commission program from 1939 to 1945.

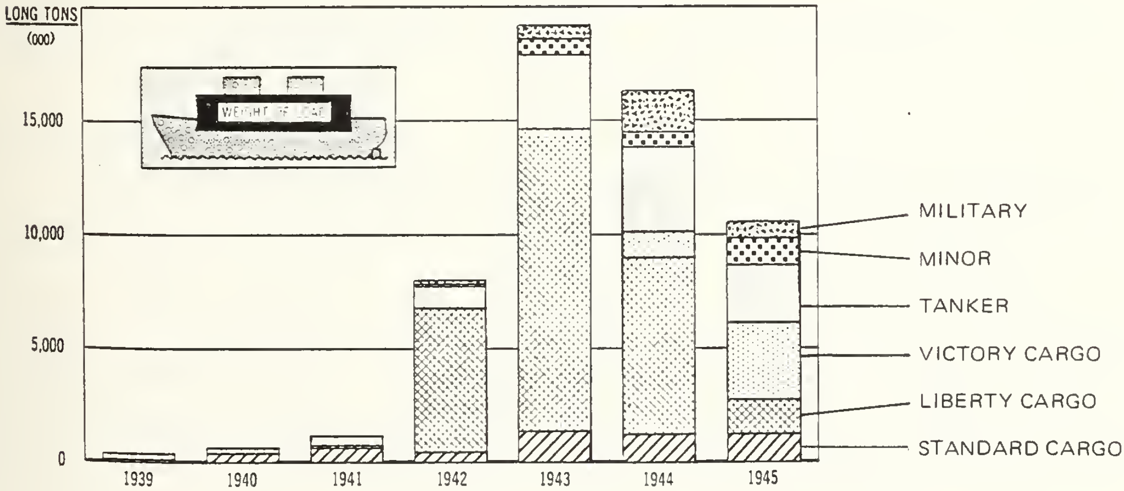

Figure 2-1. Deadweight tons of ships produced in the Maritime Commission program.(20)

Although deadweight tons were heavily publicized during the war in order to stress the need for cargo-carrying capacity, displacement tons are a more accurate measure of industrial output. Figure 2-2 shows the displacement tonnage produced on a monthly basis from 1942 to 1945. Liberty ships displaced approximately 3500 tons each.

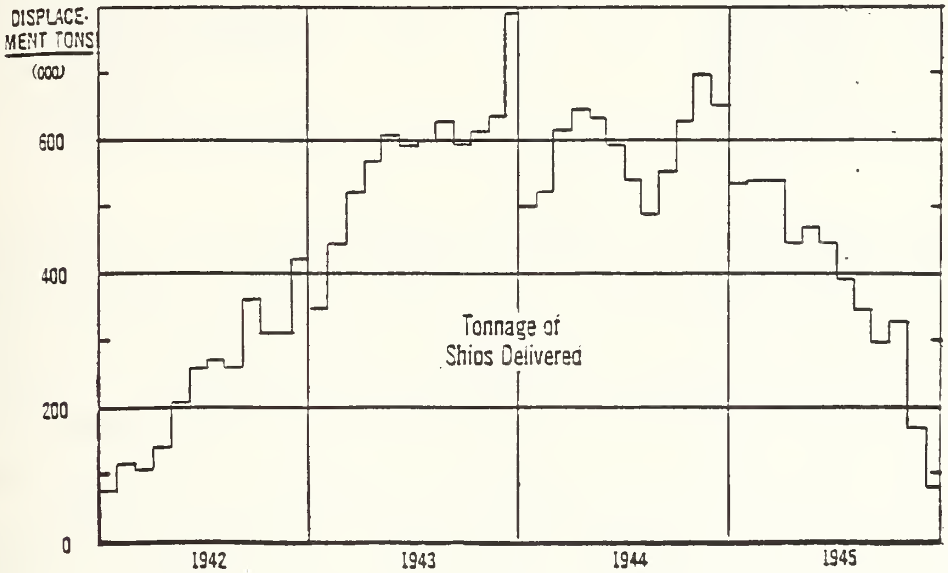

Figure 2-2. Displacement tons of ships produced in the Maritime Commission program.(21)

2.4 Facilities Expansion

The facilities expansion that enabled these tremendous production achievements is noteworthy and will be outlined here. As noted in Table 2.1, only 7 companies were building ocean-going ships in the late 1930's. As shipbuilding increased under the Maritime Commission's long-range program, however, this number grew rapidly, and 11 other companies could be added to the list by the end of 1940. They are listed in Table 2.3. None of these, nor any of the previous 7, had any idle shipways in the fall of 1940. When the first wave of expansion began, therefore, it was necessary to expand even further. Some existing yards were enlarged, and 8 "emergency" yards with a total of 61 shipways were started

Table 2.3. New shipyards by the end of 1940.[22]

Company	Shipyard
Tampa SB & Engineering	Tampa, FL
Ingalls SB	Pascagoula, MS
Pennsylvania Shipyards	Beaumont, TX
Consolidated Steel	Long Beach, CA
Western Pipe & Steel	San Francisco, CA
Moore DD	Oakland, CA
Seattle-Tacoma SB	Tacoma, WA
Pusey and Jones	Wilmington, DE
Gulf SB	Chickasaw, AL
Alabama DD & SB	Mobile, AL
Welding Shipyards	Norfolk, VA

in early 1941. These are listed in Table 2.4. As shipbuilding requirements continued to grow through the fifth wave of expansion, the Maritime Commission attempted to meet the requirements by increasing productivity, adding more shipways to existing yards, and building new yards. Since building ways were the critical facilities limitation, time on the ways became the critical measure of productivity. At the beginning of the war, contracts specified delivery schedules that called for an output of 2 ships per way per year. By mid-1942, the goal was 6 ships per way per year. The actual production rate, however, was increasing more slowly than desired, so additional yards and ways were built. Figure 2-3 shows the location of the U.S. shipyards producing ocean-going vessels by the end of 1942 as well as the total number of shipways either in use or under construction.

Table 2.4. Emergency shipyards.[23]

Company	Shipyard	Management
Todd-Bath	South Portland, ME	BIW
Bethlehem-Fairfield	Baltimore, MD	Bethlehem Steel
North Carolina SB	Wilmington, NC	Newport News
Delta SB	New Orleans, LA	American SB
Houston SB	Houston, TX	Todd
California SB	Los Angeles, CA	Kaiser
Todd-California SB	Richmond, CA	Kaiser
Oregon SB	Portland, OR	Kaiser

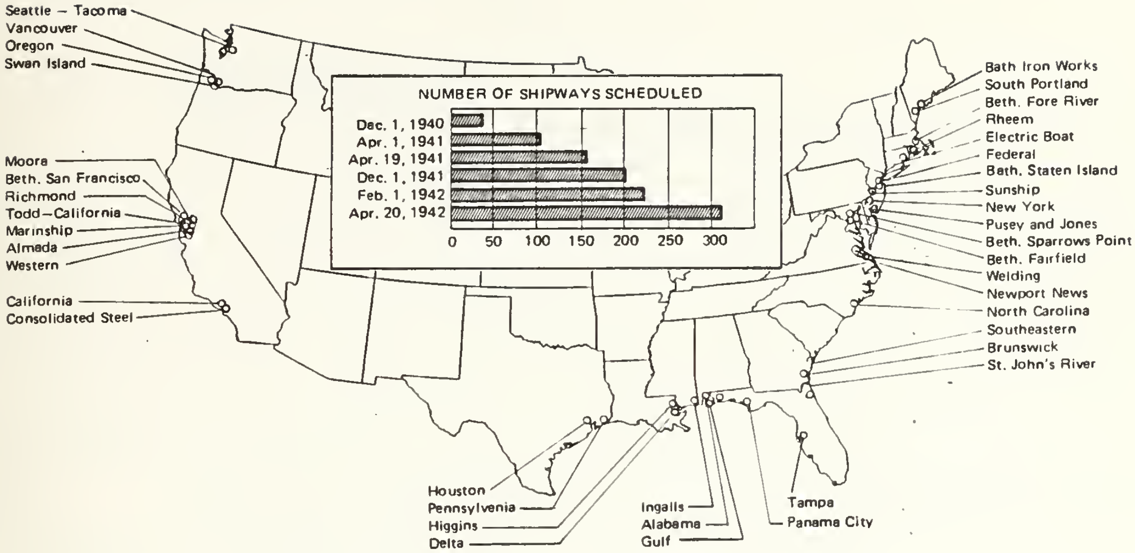

Figure 2-3. Shipyards and shipways.(24)

Management of the new yards came primarily from established shipbuilders. However, the most spectacular productivity gains were being made by a newcomer named Henry J. Kaiser. Although Kaiser was new to shipbuilding, he had numerous other industrial achievements, including the San Francisco to Oakland Bay Bridge and the Hoover, Bonneville, and Grand Coulee dams. He originally became involved with shipbuilding through joint ownership of the Seattle-Tacoma yard with Todd, and by the end of the war he owned and managed 7 shipyards and shared ownership in 3 others. The 7 under his management were Portland (Oregon), Vancouver (Washington), Swan Island (Oregon), and 4 yards in Richmond (California). Another name worth noting is that of Andrew Higgins. Higgins was a Louisiana industrialist who, in 1942, had a contract to construct a 44-way yard in New Orleans. His intention was to produce ships on assembly lines, but his contract was cancelled in July of 1942 because of

shipbuilding overcapacity. The design of the New Orleans yard will be discussed later in more detail.

2.5 Shipyard Productivity

Increases in shipyard productivity were heavily relied on in the third, fourth, and fifth waves of expansion to meet the new production goals. Indeed, the productivity achievements seem phenomenal by today's standards. Liberty ships averaged only 28 days on the ways at the end of 1943, and another 13 days in outfitting. They were thus being produced at a rate of 13 ships per way per year. The record for an individual ship was 4 days on the ways at Kaiser's Richmond No. 2 yard, and the record sustained rate was 17 days on the ways at Kaiser's Portland yard.

There were 6 primary factors which enabled the incredible shipbuilding accomplishments of World War II. They were:

(1) Design simplification
(2) Standardization
(3) Quantity production
(4) Prefabrication
(5) Technological innovation
(6) Sense of urgency

2.5.1 Design Simplification

It should be recalled that the Maritime Commission's original long-range program called for the construction of relatively high performance standard-type ships. However, when the sudden need arose for large numbers of ships during the first and ensuing waves of expansion, performance was dropped in favor of producibility. The Liberty ships were based on a very simple British design that had evolved over time to include a number of features which facilitated production. The Liberty

ships went even further, though, and incorporated the following design simplifications:

- Eliminated most compound curves at the bow and stern
- Square hatch corners
- Simplified single deckhouse
- No weather deck camber between hatches
- Straight camber from the hatches to the sides
- No emergency diesel generator
- No spare anchor, reduced anchor chain length

The ships would be slow and outdated from the start, but at least they could be built at the desired rate. The strategy was well explained in the House Appropriations hearings in January 1941:

> The design is the best that can be devised for an emergency product to be quickly, simply, and cheaply built. They will be constructed for the emergency and whether they have any utility afterward will have to be determined then.[25]

As the war grew on, however, Liberty ship construction gave way to more complex types. Figure 2-4 shows the types of ships in construction between 1941 and 1945, and it is clear that construction difficulty increased after 1943. The Maritime Commission estimated the construction manhours per displacement ton for each ship type as a measure of construction difficulty. These estimates were 158 for tankers, 184.5 for Liberty ships, 190.4 for standard cargo ships, 219 for Victory transport ships, and up to 564 for the more complicated military types. This shift to more difficult ships explains why there was almost no productivity increase from 1943 to 1944. Given that the shipyards in 1943 were hampered by inexperience and yard construction still in progress, it would be reasonable to expect a significant productivity increase in 1944. However, 1943 averaged 195.3 manhours per displacement ton, and that figure increased only to 202 in 1944, not a statistically significant change.

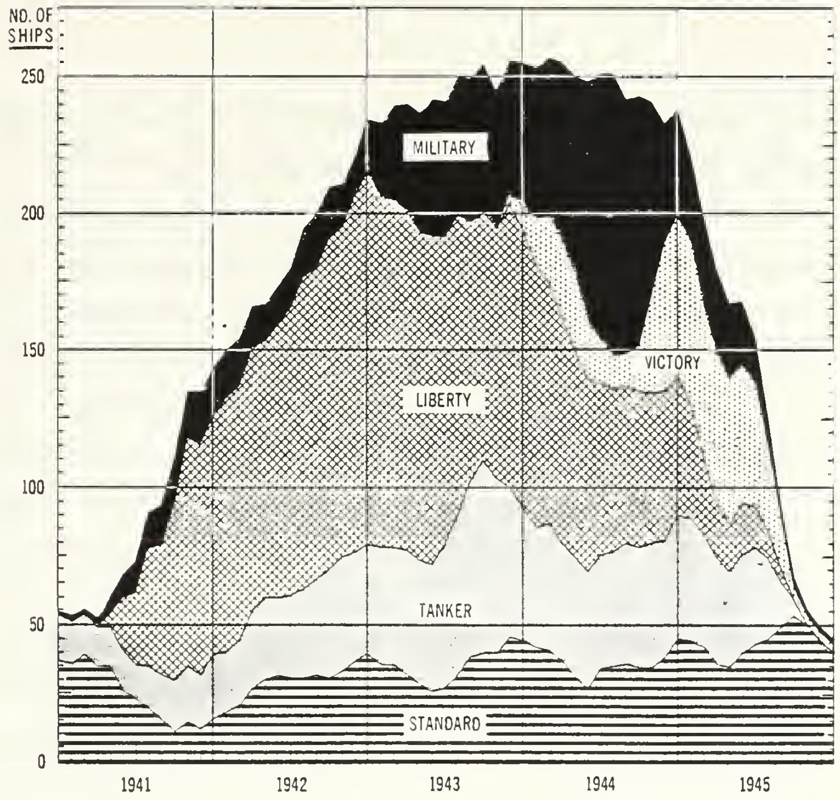

Figure 2-4. Types of ships in construction in the Maritime Commission program.(26)

2.5.2 Standardization

Standardization was identified early on by the Maritime Commission as one of the keys to a successful massive building program. It was achieved on the large scale by building all the ships of a class in all shipyards to the same design plans--there was no custom tailoring during the construction process. If any modifications were desired, they were made afterwards to the completed ship. This contrasted with the British practice of having one design for each yard. Nationwide standardization had 2 primary advantages. First, drawings could be easily reproduced for utilization by other yards. Second, it enabled a much more efficient procurement system to be enacted. Rather than have each yard purchase the materials and machinery to build the ships, the Maritime Commission (through the naval architectural firm of Gibbs and Cox) acted as the

central purchasing agent. In an atmosphere in which competition for materials was intense and in which material suppliers were stretched well beyond their normal capacities, maintaining central control of material both provided a more orderly, efficient system and minimized the disruption caused by shortages. "The procurement of components could be organized in a steady, flexible flow from a number of vendors supplying interchangeable articles to a number of shipyards."[27]

This concept of interchangeability received considerable attention from the Maritime Commission. The immense demand for shipbuilding components necessitated multiple suppliers, which could easily degrade standardization. The Maritime Commission avoided this by having all the suppliers modify their designs just enough so that the major components were interchangeable. Consider boilers and soot blowers, for example. Babcock and Wilcox, Combustion Engineering, and Foster-Wheeler made the boilers for the 200 American ships of the first wave of expansion. The shipboard boiler arrangement and the boiler components were modified from the British design so that the parts of all 3 manufacturers were interchangeable. Diamond, Vulcan, and Bayer were the 3 vendors supplying the soot blowers, and they all modified their designs enough so that any of the 4 main components (head, element, wall box, and bearings) could be interchanged and used with any boiler or piping system. Another good example is the propulsion engine. The General Machinery Corporation supplied the engines for the 60 British ships in the first wave. For the 200 American ships, Gibbs and Cox called together the General Machinery Corporation and 10 other potential vendors to decide on a simple, standard design. The agreed upon design allowed for some variation from vendor to vendor, but the major parts in all the variations could be used in any of the other designs. Producibility of each of these parts also played a major role in the engine design and was much more important than performance.

> A standard reliable product that could be built in a minimum amount of time was what was wanted. It was not doubted that this engine could be improved upon, but improvements were not wanted.[28]

Another design characteristic was the attempt to standardize various items within each ship. For example, the number of steel plate gauges was reduced from 75 to 27. This undoubtedly led to a sub-optimal design from a weight and performance standpoint, but certainly simplified supply and production.

2.5.3 Quantity Production

Standardization is intimately linked with quantity production, for without both, neither is particularly advantageous. The two primary advantages of large quantity production were that it allowed the shipyards to benefit from a learning curve, and it changed the economics of the process so that assembly lines with special tooling became feasible. The learning curve is best illustrated by the length of time it took to build Liberty ships. The first Liberty ships in 1941 took about 250 days from keel laying to delivery. By late 1943, the average time was 42 days. This was partly due to better organization of the shipbuilding process, thereby allowing higher manning levels and requiring fewer manhours per ship, and partly due to finishing construction of the shipyards. Construction time and manhours per ship are shown graphically in Figure 2-5. The average manhours per ship were more than cut in half, while building time was cut by about four-fifths. This difference, which is due to higher manning levels, was a result of extensive prefabrication and will be discussed in the next section. The construction time learning curve is demonstrated even more dramatically by looking at successive ships within a shipyard. Figure 2-6 shows the time on the ways for the first 20 Liberty ships built in Kaiser's Portland yard and the average for all shipyards. Also included are the manhours per ship. As can be seen, the great majority of the improvement came in the first 4 or 5 ships, although this is exaggerated somewhat by the fact that the first ships were generally produced while the yard was still under construction.

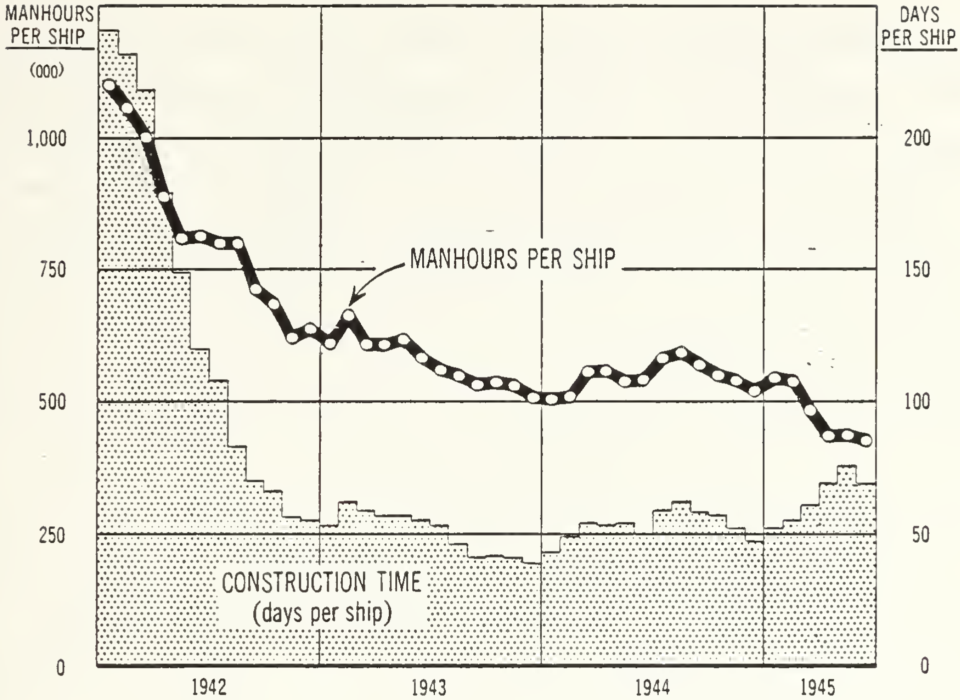

Figure 2-5. Construction time (keel laying to delivery) and manhours per ship for Liberty ships.(29)

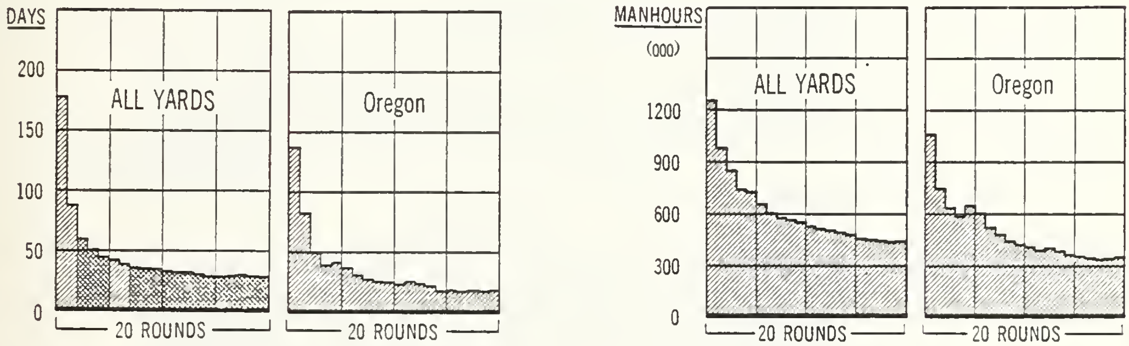

Figure 2-6. Time on the ways and construction manhours for first 20 Liberty ships at Portland and all yards.(30)

The learning curve is a result of workers and management doing the same thing many times and simply getting better at it each time. The success of the Liberty ship program "depended, first of all, at least from an engineering standpoint, on having standardized the product. Speed in production came from building the same design over and over again with the continuity that made it possible both to learn from experience and to plan ahead."(31) Without standardization, repetition and its advantages are diminished. This is demonstrated by the impact on productivity of changing from constructing Liberty cargo ships to other types. Figure 2-7 shows productivity (measured in displacement tons produced per million manhours) on a quarterly basis in Kaiser's Portland yard and in Calship. There was, in both these yards as well as all others, a drop in productivity precipitated by a product change, followed by an increase in productivity as the yards benefitted from the learning curve on the new product. The sharp drop in mid-1945 was due to the winding down of the shipbuilding effort as the war came to a close and it became clear that the shipbuilding capacity of the country was greatly overextended.

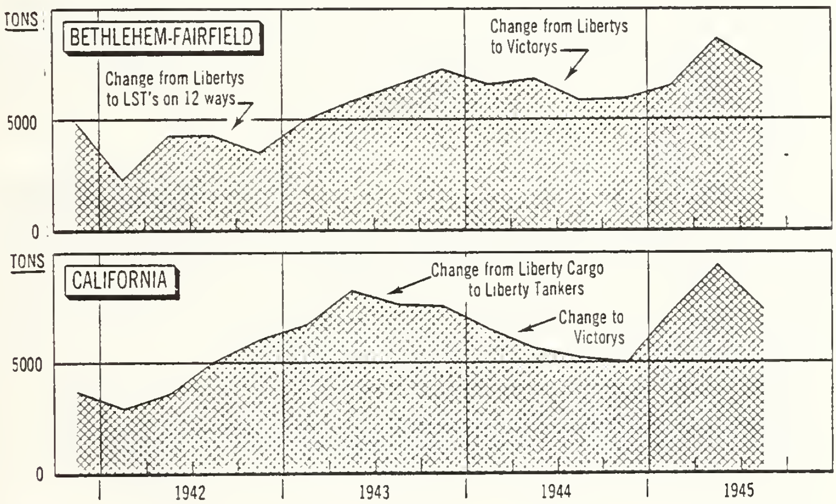

Figure 2-7. Impact of ship-type changes on productivity.(32)

The second major advantage of quantity production, assembly lines with special tooling, was also closely aligned with prefabrication. The best demonstration of assembly lines in World War II shipbuilding occurred inside the fabricating shops. Specialization of bays within the shops became common practice, and each bay tended to develop assembly line techniques to build its product. A bay that just did double bottoms, for example, would quickly learn the most efficient procedure for building them and would organize itself in a manner that effectively followed that procedure. Virtually all shipyards developed areas devoted to building the prow and forepeak sections, and devoted other areas to anything from tank tops to corrugated bulkheads. This lead to the use of hard tooling to support the specialized functions of each assembly area. Flame cutting torches, for example, were often mounted on tracks that cut the same pattern over and over again. Bethlehem Steel installed special equipment that produced 120 Liberty ship rudders per month. In general, however, shipyards were not mass producing ships or ship components in the same way that Detroit was mass producing cars. Shipyard batches were in the hundreds rather than tens of thousands, which ordinarily would limit the investment a shipyard could reasonably make in expensive equipment. Since schedule was more important than cost, though, it is likely that some facilities investments were made which wouldn't have been made on the basis of economic analysis alone.

2.5.4 Prefabrication

As was alluded to in the discussion of assembly lines, extensive prefabrication was used in building World War II ships. There had been much prefabrication in World War I shipbuilding, even to the extent of the steel plates arriving at the shipyards already cut and drilled for riveting (and frequently already riveted), so prefabrication was a logical way to approach the World War II shipbuilding challenge. Additionally, throughout the first part of the war, the number of shipways was the limiting factor in ship production. Time on the ways

was therefore at a premium, and this encouraged prefabrication. The ships were built in modules away from the shipways, then quickly assembled on the ways and launched. The average building time for all of 1943 was 35 days of fabrication and assembly, 40 days on the ways, and 10 days in outfitting. Fabrication and assembly were not complete at 35 days, but they had progressed far enough to allow rapid erection on the ways. The relation of fabrication, assembly, and erection at Calship is shown in Figure 2-8. The closeness with which assembly and erection

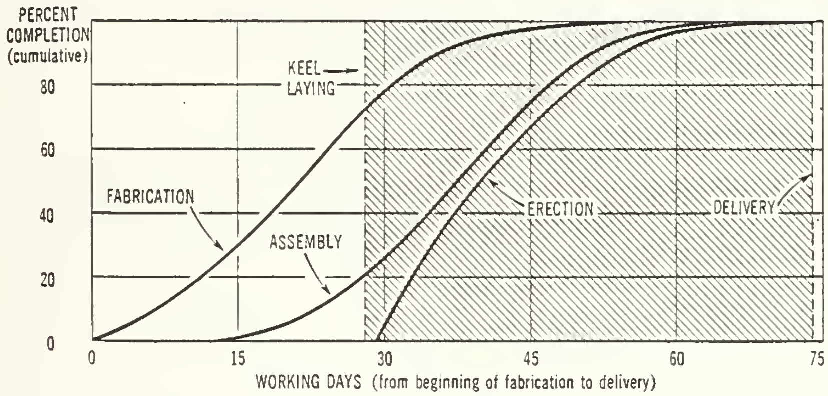

Figure 2-8. Construction stages of Liberty ships at Calship.(33)

occur--almost simultaneously with assembly just leading erection--indicates that there was probably much less in-process inventory than at Bethlehem-Fairfield, which is shown in Figure 2-9. Both shipyards had almost identical time on the ways throughout the war, yet Bethlehem was already over 80% complete with assembly prior to keel laying, whereas Calship was only 20% complete. As shown on the graph, material was 100% received prior to start of fabrication at Bethlehem-Fairfield.

Prefabrication necessitated dividing the ship into modules, which today is referred to as zone construction. Each shipyard was free to define the module boundaries in a way best suited to that yard's crane and storage area capacity. Bethlehem-Fairfield had large storage areas and prefabricated many units including 22-ton innerbottom units and 49-ton forepeak sections. The largest prefabricated unit was the 210-ton

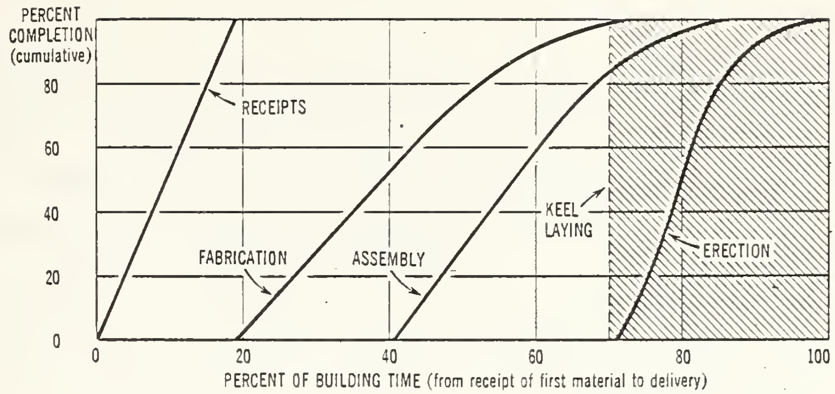

Figure 2-9. Construction stages of Liberty ships at Bethlehem-Fairfield. (Different abscissa from Figure 2-8).[34]

deckhouse at Kaiser's Vancouver yard. The deckhouse was assembled on a 4-station assembly line, each station being at the end of a subassembly line, then was placed on the ship after launching. South Portland, Maine, on the other hand, had very little storage area and did not use prefabrication extensively. Although productivity data was unavailable for South Portland, manning data shows that the yard employed only 710 men per way, compared with Kaiser's Portland yard which employed 2400 men per way, the highest of all yards. Conversely, Portland employed the fewest men per ship delivered, an indication of exceptional productivity. Although part of this difference was due to more extensive back-shift manning at Portland, it nevertheless points out a significant advantage of prefabrication--when more work is occurring away from the actual hull, more persons can be working on the ship in less crowded and better controlled conditions. Furthermore, prefabrication units could be oriented in more favorable positions for welding or doing other work, whereas the assembled ship was rather inflexible in this regard. Special tooling was also much easier to apply in the shop than on the ship.

It is unclear from the available data how much outfitting prefabrication there was. Structural prefabrication was practiced extensively, and it is safe to assume that many of the prefabricated units contained machinery, but the extent of piping, ventilation, and other system

installation is not known. Outfitting, though, was probably not the critical issue on those ships that it is today on naval vessels, since cargo ships and tankers tend to be almost all structure. Some World War II yards, nevertheless, did use an innovative outfitting technique known as progressive outfitting.[35] Each berth at the progressive outfitting piers specializes in one trade, such as electrical work. While a ship is moored at that berth, all electrical outfitting is completed. The ship then moves to the next berth where all piping is completed, and so on. All ships in outfitting must shift berths at the same time, so a great deal of workload balancing is required. Outfitting was completed in an average of ten days in 1943.

2.5.5 Technological Innovation

Welding was the one major technological innovation that was used extensively in World War II shipbuilidng. It was considerably faster than riveting and produced ships that were much lighter. The first all-welded C3 ship, the Exchequer, was 600 tons lighter than other C3's. In production, welding replaced one joining method with a faster method and enabled the use of automatic welding machines in panel assembly lines. One aspect of welding that deserves special note is the lack of quality workmanship that it was frequently characterized by. Quality assurance procedures were not yet well developed, so many of the welds made on ships were defective. This led to major structural failures in 25 merchant ships, 8 of which were lost at sea. The problem was brought under control in early 1944 by implementing some design changes and stressing better welding practices.

2.5.6 Sense of Urgency

This section includes all of those difficult to define yet very significant factors which were a direct result of the U.S. being at war. Three factors stand out in their importance; worker motivation, less red tape, and a sense of common purpose. The emotions of the war gripped

the nation after Pearl Harbor, and many shipyard employees felt directly responsible for the war's outcome. As a result, they simply worked harder. The decreased red tape involved in making decisions and getting action started allowed events to occur with speed that is almost incomprehensible by today's standards. For example, on March 2, 1942, during the fifth wave of expansion, the Maritime Commission sent telegrams to Kaiser's subsidiary companies requesting proposals for a new west coast shipyard. Ten days later, one of the companies had a plan and a contract to build Marinship in Sausalito, California. The yard was completed and delivered 5 ships that same year. Finally, the sense of common purpose was undoubtedly a factor in facilitating agreements on design compromises between competitors.

2.6 Shipyard Design

The vast expansion of shipbuilding facilities in World War II provided the opportunity to examine the various aspects of shipyard layouts that affected productivity. Perhaps the two most important features that experience proved to be necessary were large areas of open space between the ways and the fabricating shops, and a layout that facilitated a straight flow of material. The extensive prefabrication drove the need for considerable space at the heads of the ways. Scheduling in the shipyards did not have time to develop into a system where prefabricated units were finished in the shops just in time to be erected on the ways. Everyone was in the mode of working as fast as they could, so a considerable in-process inventory of prefabricated units tended to collect at the head of the ways. Yards which had not planned adequately for this became cramped and very hampered by it. Kaiser built his first yards with 300 to 350 feet at the head of the ways, but later found that even that was insufficient and built his later yards with 500 feet. The yard at Brunswick, Georgia, held the spaciousness record with 1500 feet between the ways and the shops. In designing the material flow in the yards, it was important to prevent loops in the flow, such as locating an

assembly shop behind a fabricating shop. Imperfect layouts could nevertheless be compensated for by careful planning. Kaiser's yard at Portland, Oregon, had just such a loop in its material flow, yet it ended up setting the record for sustained production speed.

Prefabrication also led to the development of specialization and production lines. In Kaiser's Swan Island yard, for example, there were 11 bays in the assembly building. Three of these fabricated corrugated bulkheads exclusively, two did shell sections, one did tank top sections, and five did miscellaneous bulkhead and dock sections. Production line design involved the arrangement of the various fabrication and assembly bays in such a manner that workpieces would move through a series of workstations and end up at the head of the shipway. The shipyard would then consist of a series of these assembly lines, all converging at the erection site. The ultimate in assembly lines was the design of the Higgins yard in New Orleans. Andrew Higgins had been tremendously successful producing small craft for the Navy using production line techniques modeled after the automobile industry. He decided to attempt the approach with larger ships, and in March of 1942 was awarded a contract for shipyard construction in New Orleans and production of 200 Liberty ships. His plan was to have 4 parallel assembly lines, 2 on each side of the fabrication buildings. Each line was to have platforms that started with the midship sections on them, then added sections as the platforms moved through 11 stations toward the sea.

> The workmen in the fabricating and assembly shops would stay in one place doing one kind of work and their product would be put together so as to be added to the ship in large sections as it went by, moving down the assembly line to the launching basin.(36)

The Higgins plan was extremely popular, not only in Louisiana but also throughout the country. The decision to cancel the contract was therefore not well received and was met with everything from public uproar to congressional investigations. From an engineering standpoint, it is

indeed sad that the contract was cancelled. Although construction of the yard had run into a number of unexpected difficulties, it is likely that it would have eventually produced ships very effectively. The concept is not unlike the extrusion construction method used today in some Scandanavian yards, wherein the ship is gradually pulled out of a fabrication building as hull blocks are added on sequentially.

2.7 Summary

The spectacular shipbuilding accomplishments of World War II were the result of all those items previously discussed, although it is difficult to quantify the effect of each one individually. Both the ship and the shipbuilding process were optimized for producibility. The ship was optimized by making it simple and keeping to a standard design. The process was optimized by using extensive prefabrication, welding, and producing the ships in large quantities. Ships were built in units, and each unit was broken down into assemblies that were produced using assembly line techniques. Furthermore, shipyard design was optimized since the new yards had the benefit of being built with high volume, rapid ship production in mind from the very start. The designs reflected the importance of prefabrication in the large space they allocated for assembly storage, and the importance of organized assembly line techniques in their straight through material flow. It is very difficult to estimate the degree to which each of these factors was responsible for the overall success, let alone how much was due to the intangible sense of urgency. It has been estimated, though, that multiple production alone increased productivity by 100%. This is based on an examination of manhours per ship, excluding the first ship in each yard (which was generally built before the shipyard was even finished). Specifically, productivity increased 93% from the second to the thirteenth ship, and another 6% from the thirteenth to the twenty-sixth ship. This increase could be directly attributed to the learning curve, but even that is difficult to isolate from the other factors since it was prefabrication that organized the

process in such a way as to have the same workers performing the same job over and over again. Once could only speculate on how effective a learning curve would be in the absence of such a well-organized process.

The shipbuilding cost breakdown during the war was not significantly different from what it had been previously. The cost of the average wartime ship was 41% material, 41% labor, and 18% overhead, compared to 40, 35, and 25 before the war. These figures are not totally out of line with shipbuilding today, although there has been a shift from labor to material costs.

In attempting to apply the lessons of World War II today, some significant differences arise. Several of the factors which contributed to productivity then are simply nonexistent or even undesirable now. First, design simplification cannot be carried to the extreme that it was for the Liberty ships. U.S. shipbuilding today is almost all military, and military ships demand performance. Producibility is becoming a major concern, but will never be the overriding concern. Second, quantity production and sense of urgency are wartime dependent. We just don't have them in peacetime, although the use of group technology to artificially boost production quantity will be discussed. Third, although welding technology has advanced tremendously, so have the quality assurance requirements. It's probably safe to say that welding is a more cumbersome process today than it was in World War II (primarily due to the use of higher strength steels). That leaves standardization and prefabrication as the only areas that are fully within our control. These will be discussed in detail in later chapters.

CHAPTER 3

NAVAL SHIP DESIGN AND CONSTRUCTION

3.1 The Naval Ship Design Process

The process of ship design and construction is extremely lengthy. The lead ship of a class of destroyer-sized naval vessels requires from 5 to 10 years to design and construct, which is often preceded by 5 to 10 years of development of some of the more complex systems on board (such as weapons and electronics).[37] This chapter will begin with an overview of the naval ship design and construction process, then will center on the costs involved in naval shipbuilding. The intent is to delineate the various costs and identify the major cost drivers.

Naval ship design occurs in 5 phases: feasibility studies, conceptual design, preliminary design, contract design, and detailed design. The time sequence of these phases is shown in Figure 3-1. During the feasibility studies phase, a number of alternate configurations are considered, and the one which will best meet the needs of the Navy is selected based on a balance between performance and cost. Performance requirements are firmed up and major technical risks are identified. The chosen configuration is then developed in the conceptual design phase enough to validate the results of the feasibility studies. Major ship systems are selected, major technical risks are resolved, and approximate weight and cost estimates are made. The purpose of the preliminary design phase is to integrate the ship systems and "achieve a complete engineering description of an integrated ship...(and) functional definition of integrated subsystems."[38] Weight and cost estimates are refined.

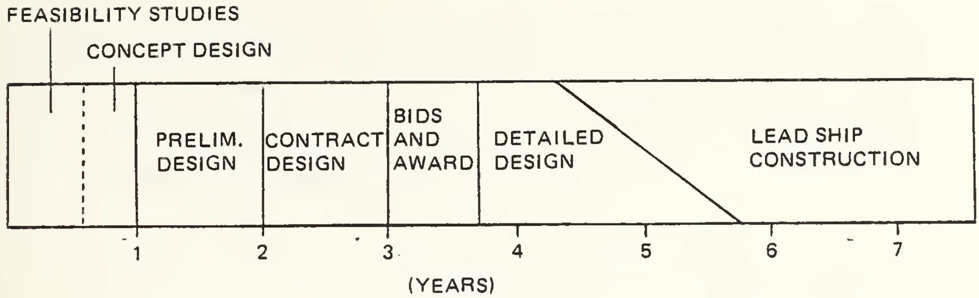

Figure 3-1. Design phases and construction for a lead ship.[39]

Contract design further refines the estimates and translates the engineering definition of the ship into a biddable package for private industry. Contracts for the FFG-7 program were cost plus fixed fee for detailed design, cost plus incentive fee for lead ship construction, and fixed price for follow ship construction.[40] Although this changes every decade or so, all the design work up to this point would be done by NAVSEA or its design agents. Frequently industry is consulted, though, during the contract design or even preliminary design phase in order to help incorporate producibility considerations into the design. Following contract bids and award, the lead shipyard does the detailed design, which consists of both system design and production of working drawings. The detailed design serves as the basis for actually building the ship. As shown in Figure 1, there is a considerable overlap between detailed design and lead ship construction. This is characteristic of conventional shipbuilding methods, but, as will be discussed in the next chapter, is not desirable in advanced shipbuilding methods.

During ship construction, the shipyard purchases some raw materials, such as steel plate, pipes, and cabling, with which to fabricate and assemble the ship. Other components, such as valves, pumps, and motors, are generally purchased from vendors. Such items are called Contractor Furnished Equipment (CFE). Still other components, such as most of the weapons and electronics gear, are purchased by the government and

given to the shipyard for installation. These items are called Government Furnished Equipment (GFE). Anything that has a very long lead time is generally included as GFE, since that enables the government to order it prior to contract award.

One of the inevitable results of this lengthy design and construction procedure is a strong desire to change the design during the latter stages of the process. The equipment which is being installed during lead ship construction might have been developed 10 or more years prior to that, and is very possibly already outdated. This is even more likely as the program proceeds into follow-ship construction. If an improved replacement has since been developed, the Navy may elect to issue a change order. This requires the shipbuilder to modify the detailed design and construction process enough to accommodate the new equipment or improved configuration. Change orders range from negligible to those having a major impact on the scope or nature of some portion of the work package. Typically, there are several thousand major change orders during a ship construction program.

3.2 Ship Work Breakdown Structure

Currently the Navy carries out the design process on a functional, or system, basis. The Ship Work Breakdown Structure (SWBS) is the accounting code used by the Navy and its contractors to track the weight of all physical components of the ship and the costs associated with the ship construction. The SWBS code consists of three digits, the first of which designates functional group; the second, subgroup; and the third, element.(41) There are 9 major groups, and they are listed in Table 3.1. The first 7 groups correspond to functional aspects of the ship. Everything that is physically a permanent part of the ship is categorized into 1 of those 7 groups. Groups 8 and 9 do not represent physical parts of the ship and are not used for tracking weights; they are only used for tracking the costs that are not directly attributable to the first 7 groups. The second and third digits identify a particular system or element within a group. Examples are listed in Table 3.2.

Table 3.1. SWBS major groups.

100	Hull structure
200	Propulsion plant
300	Electric plant
400	Command and surveillance
500	Auxiliary systems
600	Outfit and furnishings
700	Armament
800	Integration/engineering
900	Ship assembly and support services

Table 3.2. Example SWBS elements.[42]

111	Shell plating and framing
252	Propulsion control system
331	Lighting distribution
472	Passive ECM systems
521	Firemain and flushing system
612	Rails, stanchions, and lifelines
721	Missile launching system
843	Inclining experiment
991	Temporary utilities and services

3.3 Ship Acquisition Costs

Having reviewed the naval ship design process and cost accounting procedure, it is now possible to quantify the costs involved in naval ship construction. Specific detailed cost information is considered proprietary; therefore, the cost data in this chapter is based on several different classes of ships and is intentionally approximated. It is intended to give a general idea of the comparative costs of various aspects of ship acquisition and should not be used as a basis for more detailed analysis. The ships involved were all non-nuclear surface ships of

moderate size (no aircraft carriers). The figures best represent ships with gas-turbine propulsion plants.

The actual cost to the government of a ship over its entire lifetime is its life cycle cost, which includes acquisition cost, operating costs, maintenance costs, etc. Although acquisition cost is only about one-quarter of the life cycle cost,(43) it receives the most attention and will be the only cost considered here. Operating and maintenance costs are irrelevant to the shipbuilding industrial process and are therefore outside the scope of this thesis. Acquisition cost is essentially the price tag of a new ship. The Navy uses the "P8 Cost Breakdown" to categorize acquisition costs into 9 groups. These groups, along with their respective approximate percentages of the total acquisition cost for a typical follow ship, are listed in Table 3.3.

Table 3.3. Follow-ship acquisition cost breakdown.

Item	Description	Percent
1	Plan costs	0.5
2	Basic construction	38.0
3	Change orders	2.0
4	Electronics	14.0
5	H, M, & E	2.0
6	Other costs	1.0
7	Ordnance	30.5
8	Escalation	7.0
9	P. M. growth	5.0

Item 1, plan costs, includes the cost of producing the detailed design plans, developing test plans and procedures, and writing technical manuals. These costs are very significant for the lead ship of a class (about 9% of the total), but account for only 0.5% for a follow ship. Item 2, basic construction, includes the material, labor, and overhead costs of purchasing raw materials and CFE, fabricating and assembling the ship, and installing and testing all equipment and systems, including

GFE. Item 3, change orders, is the cost attributable to disruption of the shipbuilding process caused by Navy issued change orders. Items 4 and 7, electronics and ordnance, are GFE which together make up the combat systems suite. Item 5, hull, mechanical, and electrical, is noncombat systems GFE. It would be significant in a nuclear powered ship (since it would include the nuclear power plant), but in a non-nuclear ship it is not large and includes only a few items such as the small boats, anchors, and some navigation equipment. Item 6, other costs, is used to fund NAVSEA expenses, such as design agents. Item 8, escalation, accounts for the cost impact of inflation. That impact is felt primarily in basic construction, which typically spans several inflationary years. Item 9, program manager growth, pays for unexpected costs associated with GFE in the same manner that item 3 funds unexpected changes in basic construction.

To put these costs in perspective, items 4, 5, 7, and 9 are all GFE related and combine to make up 53.5% of the total cost. Thus, over half the cost of a ship is completely beyond the control of the industrial process of shipbuilding. The shipbuilder is responsible for the basic construction costs, which account for 38% of the price tag, and also indirectly affects the escalation cost, since the escalation rate is applied primarily to basic construction. The shipbuilder, therefore, has some degree of control over somewhat more than one-third of the total ship acquisition cost.

The next step is to divide basic construction costs into its 3 components: material, direct labor, and overhead. The U.S. Maritime Administration examined the cost division between material and labor/overhead for various ship types and other industrial products. The results, which do not include profit, are listed in Table 3.4. Including profit and using more recent data gives the basic construction cost breakdown listed in Table 3.5.

Table 3.4. Construction expenses for various industrial products.(44)

	Material (%)	Labor and Overhead (%)
Steel harbor tugs	68	32
Wood fishing vessels	67	33
Marine boilers	62	38
General cargo ships	62	38
Joiner subcontractor	60	40
Naval auxiliary ship	59	41
Naval combatant ship	55	45
Naval amphibious ship	53	47
Hatch covers	52	48
Commercial buildings	52	48
Propulsion turbine/gears	39	61
Naval submarine	38	62
Naval hydrofoil	35	65

Table 3.5. Naval combatant ship basic construction cost breakdown.

	Percent
Material	50
Direct labor	20
Overhead and profit	30

These figures are for a naval combatant ship and are only approximate. Similar breakdowns for 18,000 dwt roll-on/roll-off freighters built in 1972 in the U.S and Japan are shown in Table 3.6. The total cost of the Japanese vessel was only 60% that of the U.S. ships which was similar but not identical. For both the naval and merchant ships, direct labor costs are only a fraction of the construction price tag. The thrust of flexible automation is generally considered to be reduction of direct labor

Table 3.6. Eighteen thousand dwt freighter construction cost breakdown.(45)

	U.S.		Japan	
Material		41.1		65.4
Labor: Hull	11.5		5.0	
Outfit	7.7		7.1	
Machinery	2.3		2.9	
Other	6.2		0.0	
Total		27.7		15.0
Overhead and profit		31.2		19.6
		100.0 ($37.8M)		100.0 ($22.7M)

labor costs, which represent only 20% of the basic construction cost of a naval ship, or 7.6% of the total acquisition cost. A 50% reduction in direct labor would therefore result in less than a 4% savings in the total ship cost to the Navy. Other estimates have come up with similar results. Ray Ramsey of the Naval Sea Systems Command estimated the actual manufacturing costs of a ship to be less than 8% of the total acquisition cost.(46) Clearly, there are other major issues which must be addressed if the cost of naval ships is to be significantly reduced. However, flexible automation can also impact material and overhead costs. Excessive rework due to poor quality industrial processes can significantly increase material costs, as can inefficient utilization of raw materials due to poorly thought-out cutting plans. Overhead costs increase when poorly planned process flow lanes cause in-process inventory to pile up. Chapter 1 noted that many Japanese and European shipyards have significantly lower material and overhead costs than U.S. yards, so these cost factors should not be ignored in assessing the cost impact of flexible automation.

3.4 Direct Labor Costs

The remainder of this chapter, however, will be devoted to direct labor costs. For the sake of clarity, let us assume that we are analyzing a ship with a direct labor cost of $100 million. This corresponds to a total acquisition cost of $1.32 billion, which is excessively high for a destroyer-type ship, but it simplifies the discussion by allowing percentages and millions of dollars to be used interchangeably. It is a reasonable estimate for the price of a cruiser in the not too distant future. It is instructive to examine the nature of the work that costs $100 million both from a craft and a system point of view. A typical breakdown of labor costs by craft is shown in Table 3.7. Welding (along with burning) is shown to be the number one cost driver. However, welding is done to support a wide variety of work--hull structure, foundations, piping, sheetmetal, electrical conduit brackets, hull insulation studs, etc. A simple craft breakdown does not adequately address the issue of work content. Some additional light is shed by looking at the cost by SWBS code. The cost breakdown for the nine major functional groups is shown in Table 3.8. Auxiliary systems, which are primary piping and ventilation, are the major cost drivers. Hull structure is significant as a single category, but is much smaller than the overall cost of outfitting. This is one item which distinguishes a naval vessel from a merchant ship. Cargo ships and tankers are predominantly structure, whereas naval ships are packed full of piping systems, electrical systems, ventilation ducts, and other nonstructural components. Outfitting is even more significant for submarines.

If we further divide these major functional groups into individual elements and groups of similar elements, we get a better picture of what the real cost drivers are. Table 3.9 lists the major cost items as well as a number of minor items of interest. Recall that these figures best represent a gas turbine ship, which has no main steam or high pressure drain system and only a minimal auxiliary steam system; a conventional steamship would have even higher piping costs. Nevertheless,

Table 3.7. Direct labor costs on hypothetical naval combatant ship.

Craft	Cost ($million)
Burners/welders	16
Electricians	14
Pipefitters	14
Shipfitters	11
Sheetmetal	11
Laborers	5
Painters	4
Marine machinists	3
Other	22
Total	100

Table 3.8. Direct labor costs by SWBS for naval combatant ship.

SWBS Group		Cost ($million)
100	Hull structure	17
200	Propulsion plant	5
300	Electric plant	13
400	Command and surveillance	4
500	Auxiliary systems	18
600	Outfit and furnishings	15
700	Armament	2
800	Integration/engineering	8
900	Ship assembly and support services	18
	Total	100

piping systems are still the major cost item, followed by hull structure and electrical distribution. Painting, ventilation, foundation, and hull

Table 3.9. Major cost items on a naval combatant ship.

Element	Cost ($million)
Piping systems	15.0
Hull, decks, superstructure	11.0
Power, lighting, cableways	9.0
Painting	5.0
Ventilation	5.0
Foundations	4.0
Hull insulation	3.0
Cleaning services	2.5
Material requisition and inventory	2.0
Production planning and control	2.0
Crane and rigging	1.5
Temporary utilities and services	1.5
Scaffolding	1.0
Jigs, fixtures, special tools	1.0
Transportation	0.5

insulation are also very expensive, each being 3% or more of the direct labor cost. Although not specifically listed, lockers and shelves are fairly significant, amounting to an estimated several percent. The SWBS groups much of outfitting by compartment, making it difficult to isolate the cost of specific types of work, such as lockers. Of the $15 million for piping systems, 73% is for pipefitters, 16% is for welders, and 11% is for other trades. (Pipefitter work on nonpiping systems includes waveguides and refrigeration compressors.) A more detailed discussion of piping systems will be reserved for Chapter 5.

To summarize, direct labor costs in basic construction amount to $100 million in a $1.32 billion ship. Material costs for raw material and CFE total $250 million, and shipyard overhead costs and profit come

to about $150 million. Flexible automation has the potential to influence all of the basic construction costs, although emphasis is generally placed on direct labor cost. Outfitting dominates direct labor costs in naval shipbuilding, with piping systems being the single most expensive group of systems. Pipe fabrication and subassembly will be the subject of much more attention in later chapters.

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CHAPTER 4

SHIPBUILDING METHODS

4.1 Conventional Shipbuilding Methods

> The traditional organization of shipbuilding, dating from the days of wooden ships, was to construct the ship in place, working on each functional system of the ship in turn. First, the keel was laid, then the frame erected, and so on. When the hull was nearly complete, outfitting of the ship began. Outfitting was planned and carried out by system, as ventilation, piping, electrical, and machinery systems were installed.(47)

This organization undoubtedly grew out of the systems approach used in ship design. Ship owners think of ship performance in terms of system performance, and they define the design requirements by system. The ship designers, who are functionally oriented to begin with, therefore find it very convenient to perpetuate the systems approach in their designs and in their own organization. The Navy's use of the SWBS, as discussed in the previous chapter, is a good example of the systems nature of ship design. The systems approach was passed on to the shipbuilders via the issue of plans by system. Each system had its own drawings, and outfit drawings were generally not issued until hull construction was well underway.(48) This, together with the unionized structure of the shipbuilders, forced the utilization of a systems approach to construction.

Unfortunately, this is a very inefficient way to build ships. Nevertheless, it persisted in the United States until recently, leading naval architect Thomas Gillmer to write in 1975:

> Except for the brief period of mass produced cargo ships and smaller craft during World War II in the United States, the process of shipbuilding has been traditional, methodical, and conservative. In most cases it was and still is a slow, laborious, and very expensive process.(49)

The situation, however, has changed significantly since then. Virtually every major naval shipbuilder is adopting a zone-oriented approach to ship construction, and the results to date have been extremely good.(50) Section 4.2 will discuss zone construction and outfitting, as well as other modern shipbuilding techniques, in more detail. The impact of these techniques on design and engineering will also be examined. Section 4.3 will briefly discuss some unique aspects of naval ships that will affect the utilization of modern techniques in naval shipbuilding.

4.2 Modern Shipbuilding Methods

4.2.1 Zone Construction and Outfitting

Zone construction is based on dividing the ship into geographical units rather than breaking it down functionally by system. In other words, it is modular pre-fabrication, very similar to that used in World War II. Most shipyards already apply the zone approach to hull construction.(51) The modular breakdown for the TAO (oiler) built at Avondale Shipyards is shown in Figure 4.1.

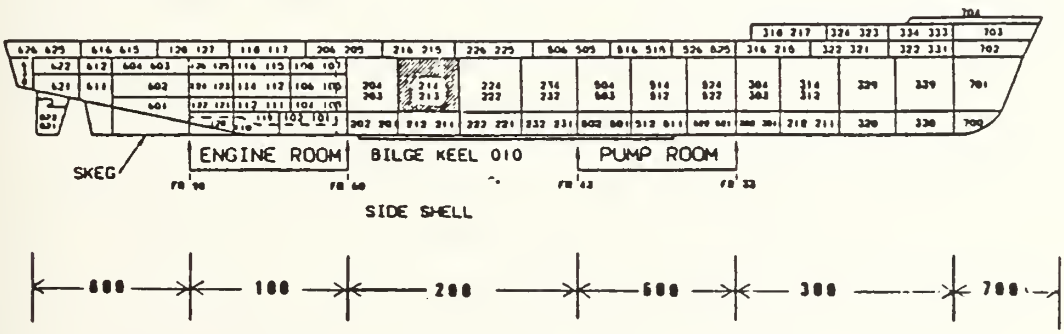


Figure 4.1. Hull block breakdown for TAO at Avondale Shipyards, Inc.(52)

Zone outfitting is more difficult to implement than zone hull construction, and shipyards are still in the process of adopting it. Its purpose is to make outfitting an integral part of the hull construction process--to outfit the modules before putting the modules together. "The driving force in zone outfitting is the installation of components at the times and under the conditions that produce the lowest overall costs."[53] The optimum time is generally while the hull block is still in the shop, before it is erected on the ways. The optimum condition occurs when the block is not crowded with other workers and when it is oriented in such a manner that workers don't have to reach up to weld, hang piping assemblies, etc. Frequently that calls for the block to be upside down. Three types of outfitting are commonly defined in the literature: on-unit, on-block, and on-board. On-unit is that outfitting done on a pre-assembled machinery package, separate from any ship's structure. On-block is the outfitting of structural blocks prior to their erection on the ways. On-board is the outfitting of structural blocks after their erection on the ways. It is still organized by zone, but requires 30% more labor hours than on-block outfitting and 70% more than on-unit.[54] On-board outfitting should therefore be limited to equipment whose size, weight, or susceptibility to damage precludes earlier outfitting, and to certain distributed systems (such as electrical cables) that are not amenable to division at block boundaries.

Avondale Shipyards, Inc., is perhaps the leader among U.S. yards in implementing zone outfitting. The increasing degree to which Avondale pre-outfits hull blocks is shown in Figure 4.2. Avondale uses the term "unit" to designate a hull block. Zone outfitting has improved Avondale's schedule and cost performance dramatically. Keel laying to launch time has decreased over 20% and launch to delivery time has decreased over 30% on non-combatant ship construction.[55] Regarding cost, Avondale was recently able to win the procurement contract for new Navy amphibious ships (LSDs) by underbidding Lockheed by about 30%, after Lockheed had already built the first three ships of the class.[56] Avondale executives cited the adoption of modern shipbuilding methods as

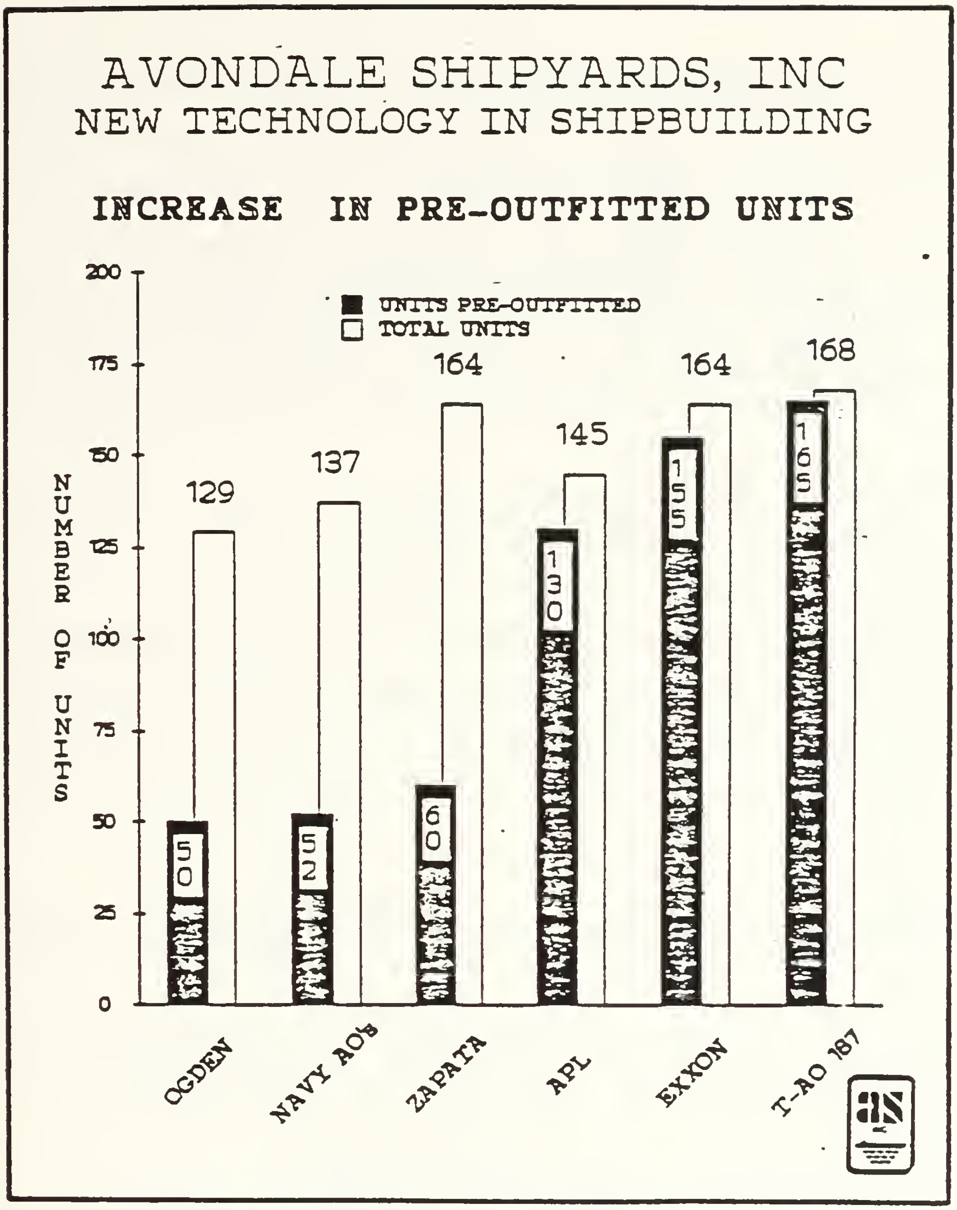


Figure 4.2. Increased use of on-block outfitting at Avondale.(57)

the primary reason for their ability to bid so low and still make a profit.

4.2.2 Process Flow Lanes

Having divided the ship into modules, it is now appropriate to look at the most efficient method for constructing each of those modules.

Modern construction techniques are premised on organizing the work by process similarities. Organizing the work into process flow lanes optimizes efficiency by taking full advantage of those process similarities.

> A process lane is a series of fixed workstations with permanent services (pneumatic, electrical, welding, etc.) and appropriate tooling and jigs to produce a category of products (subassemblies) whose fabrication and assembly involve the application of a given sequence of production processes or which involve a common set of manufacturing problems.(58)

The only process lanes in shipbuilding that the author is aware of are for structural assemblies. Avondale classifies all structural assemblies into six categories and has a separate process lane for each category. These six categories are listed in Table 4.1 along with the percentage of total assemblies that each category represents for a typical tanker. Percentages do not add up to 100 due to rounding off. Curved shell units would undoubtedly constitute a much higher percentage on naval combatant ships.

Table 4.1. Structural assembly categories at Avondale Shipyards. (Percentages are for a typical tanker.)(59)

Category	Description	Percentage
1	Flat panel units	48
2	Curved shell units	5
3	Superstructure units	29
4	Forepeak and aft peak	10
5	Engine room innerbottoms	5
6	Special units - skegs, rudders, etc.	5

The idea of process lanes is not new. It was used very successfully in World War II shipbuilding and is the basis of the assembly line technique used widely in other industries. By dedicating equipment to be used repetitively for similar tasks, equipment setup times are reduced.

Since workers specialize in doing similar tasks on similar assemblies, the learning curve is maximized. Material flow is simplified, because the material requirements of each assembly area are relatively constant and controllable. Material movements are thereby minimized, as was quantitatively substantiated by Avondale's experience. Implementation of the structural process lanes resulted in 28.4% fewer pieces of steel material being moved per week and a total distance reduction of 23.2 miles (34.8%).[60] The savings were significant in terms of both transportation costs and reduction of lost material. Figures on the total savings due to all the other advantages were not available to the author.

4.2.3 Accuracy Control

The shift to zone construction and outfitting has made accuracy a much more critical issue, since it is impossible to force-fit two prefabricated hull blocks together in the same manner that a single plate or beam can be force-fit. Accuracy control is the method of applying statistical rigor to the establishment of realistic accuracy goals and the development of procedures and controls to achieve those goals.

> Accuracy control provides scientifically derived, written, and realistically obtainable accuracy standards and goals. ... No longer are crucial judgements about accuracy left to opinions and guesses.[61]

Accuracy control utilizes checks, controls, and statistical analysis to accomplish the objectives.[62] Checks simply monitor existing processes and point out problem areas. Checks in and of themselves do nothing to improve the product. Controls improve the existing product by ensuring a minimum level of accuracy in all processes. However, it is only through the use of formal statistical analysis that control decisions can be optimized and future work can be significantly improved. In other words, statistical analysis answers the question of how accurate is accurate enough. The tolerances for each process used in making an assembly can be set so that they are all consistent and produce the

desired accuracy in the finished assembly. The control effort can be focused on those specific areas that are currently inconsistent with the overall accuracy goals and therefore offer the most benefits if improved.

The importance of accuracy control is well documented in Japan, but it is still a fairly new concept in U.S. shipbuilding. Nevertheless, research conducted by the University of Washington at Tacoma Boatbuilding Company (on the construction of Navy ocean surveillance vessels) has shown that "accuracy control is cost-effective in both the short and long terms."(63) The short-term benefit of reduced rework alone outweighed the cost of collecting and analyzing the data. The long-term benefits from optimizing the controls and possibly improving the product design are not yet known, but are expected to be much greater than the short-term benefits (based on experience in other industries). Less force-fitting due to improved accuracy will have the additional benefit of improved shock resistance--a benefit which is of considerable importance to naval ships.(64)

4.2.4 Impact on Design and Engineering

In order for shipbuilders to be fully effective at implementing zone construction techniques, ship designers must issue working plans that are zone oriented. However, the ship design process will always begin with a systems approach since that is the only practical way to evaluate ship performance characteristics. Therefore, the design process must include a transition from system to zone orientation. In the naval ship design process, this would need to occur during the latter part of detailed design. The following design phases have been suggested as the proper sequence after contract design:

- Functional design and planning
- Transition design and planning
- Zone design and planning
- Stage design and planning(65)

These phases are being used to some degree in several yards, although not formally by these names.

Functional design develops the system details to ensure that the contract specifications are met--just as detailed design has been doing. However, rather than issuing working drawings by system, each system is spatially divided into zones during transition design, and all the system segments in the same zone are combined in composite drawings during zone design. Stage design and planning adds scheduling data--showing the sequence and timing of component installation in the zone.

The impact of zone construction on design and engineering is therefore twofold. First, it requires extensive horizontal communication among the various design functional specialists. Structural designers, electrical designers, ventilation designers, piping designers, and others must work closely together as a team to optimize the arrangement of all the systems within the zone. This teamwork provides the opportunity to produce a much better overall design than in the past, when systems were routed independently of one another (only giving attention to preventing physical interference).

Second, the amount of engineering effort is increased substantially, since it must both transition to zone orientation and incorporate scheduling data. Furthermore, the engineering effort must be heavily front-loaded. Outfitting plans cannot lag behind hull plans as they did in conventional methods. All system functional designs must be completed in time to support transition and zone design. Quantitatively, at Avondale, the total engineering manhours on noncombatants increased from 350,000 to 500,000 with the adoption of zone construction and outfitting. The additional front-loading of the engineering effort caused the average engineering manhours per month prior to start of prefabrication to more than double, from 15,000 to 33,333.[66]

4.2.5 Group Technology

Group technology (GT) has been described as the "manufacturing philosophy which identifies and exploits the underlying sameness of parts and the manufacturing processes."[67] It is a method of grouping parts or assemblies together into families that share common design or manufacturing attributes. If the family members are similar enough from a

manufacturing standpoint, then they can be manufactured together as a batch, and some of the advantages of quantity production can be achieved. Identifying design similarities is aimed primarily at reducing the number of new designs. GT application to design will be discussed first.

There is a natural tendency in shipbuilding and every other industry to continually design new parts and assemblies for use in new products. Existing parts (perhaps with minor modifications) might do the job, but the designer is not always aware of all the existing parts and might not have an incentive to use them. "Design engineers are creative and talented people. Being creative does not lend itself to the adoption and continued use of mundane standards."(68) Furthermore, the cost of part proliferation is generally grossly underestimated.(69) However, studies show that there are only 2,000 to 6,000 truly unique designs in any given industry,(70) and that the cost of designing a new part averages $1,900.(71) Using GT to identify existing parts that meet a design need has been shown to reduce new part designs by an average of 5 to 10%, and in some cases as much as 40%.(72) Although shipbuilding use of GT is just beginning, the savings in other industries have been significant. Pitney Bowes, for example, reduced new part costs by $200,000 annually.(73) GT adds both the capability and the incentive to use existing parts. By establishing families of similar parts, it becomes feasible for the designer to search through a given family to find what he needs (rather than having to search through all the parts); if a family becomes excessively large, it draws attention to the design redundancy.

Many parts that are dissimilar in design are nevertheless very similar in their manufacturing processes. GT can be used to identify these similarities by forming families based on manufacturing attributes. This application will be discussed in much greater detail in Chapter 6.

GT uses a coding and classification scheme to identify the desired similarities. Each part or assembly is described by a code, each digit of which describes some particular aspect of the part (such as material,

thickness, machining tolerance, surface treatment, etc.). All the parts with the same given digit or group of digits form a family. Codes can be designed as polycodes, monocodes, or a hybrid mixture of the two.[74] All the digits are independent of one another in a polycode. For example, a "3" as the fifth digit would always mean the part material is stainless steel. In a monocode, the meaning of each digit depends on the preceding digits. The same "3" might mean stainless steel if the third digit were a "1", but it might mean a tolerance of ± 0.001 inches if the third digit were a "2". A hybrid code contains some dependent and some independent digits. Most codes in use are hybrid or polycode. Several used in shipbuilding will be discussed briefly.

Most GT applications to shipbuilding so far have been in the area of structures, although pipe fabrication has been mentioned in the literature as another potential area.[75] Several structural codes have been developed in Europe, including ones by personnel of the British Ship Research Association and The University of Strathclyde in Glasgow, Scotland. These are both polycodes of ten and nine digit length, respectively. The attributes identified by the latter code are listed in Table 4.2.

Table 4.2. Ship structures code developed at University of Strathclyde.[76]

Digit	Attribute
1	General classification
2	Shape before forming
3	Forming
4	Holes and slots
5	Edge preparation
6	Material and finish
7	Thickness
8	Length
9	Width

It is clearly a manufacturing code, since the digits primarily describe manufacturing processes rather than design form, fit, and function.

Some codes attempt to include both manufacturing and design attributes. One such code, MULTICLASS, was developed at the Organization for Industrial Research (OIR) in Waltham, Massachusetts.(77) The MULTICLASS code has 32 digits that can take on a variety of meanings, depending on the desired application. For machined parts and sheet metal assemblies, 18 of the digits are defined by OIR, with the others left to the user's discretion. Other applications, such as electronics parts, do not yet have an established code structure. The software program for family grouping is called MULTIGROUP and can handle whatever digits become assigned to the code. Electric Boat is using MULTICLASS to code all the machined and sheet metal parts used in submarines. When coding is finished, EB expects to have 25,000 different parts used in Groton and 18,000 different parts used in the Quonset Point facility.(78) This is substantially more than the 2,000 - 6,000 different designs that are generally believed to exist. The author is unsure how much of this is due to design redundancy and how much is due to the complex and diverse nature of submarine design.

4.3 Applications to Naval Shipbuilding

The complex and diverse nature of submarine design is also true of all naval combatants and is the primary feature that distinguishes them from merchant ships. Naval combatants are multi-mission ships that contain many complex systems, support a large crew, and operate in the most adverse of environments. From a construction standpoint, this complexity manifests itself in a much larger amount of outfitting than is characteristic of merchant ships. Much of this outfitting is electrical, and electrical zone outfitting is limited by the current inability to divide electrical cables into zones. That might change as cable technology advances, but for now all shipyards pull cables after the hull blocks are joined together (on-board outfitting).

Additionally, naval combatants generally stress performance above all else. Although producibility is receiving increased attention, naval combatants will always contain performance features that make them more

difficult to build. A higher percentage of curved structural panels, tighter quality assurance standards, and shock hardening requirements are but three of many examples. The Navy uses military standards and specifications to ensure that the desired performance is achieved. While many milspecs are necessary, commercial standards should be relied on whenever possible. A conversion to commercial standards is currently underway as part of the milspec improvement program.

Closely related to complexity and performance is the extensive system testing that must be done on naval ships. While some hydrostatic tests and equipment check-outs can be accomplished on-block, system operational tests can only be done on-board. Tests that could be affected by the minor changes in hull shape that occur when the ship becomes waterborne, such as combat systems alignment, must be done after launching.

Finally, one aspect of the naval ship design process that can have a significant effect on construction is the large number of change orders. As explained in the previous chapter, change orders are used to incorporate new technology and other improvements into a ship already being built. The shift to zone outfitting and the front-loaded design and engineering effort will exacerbate the disruption caused by change orders. The Navy will have to consider that increased level of disruption in future decisions, and should make every attempt to minimize the number and scope of change orders.

These naval combatant features make the application of modern shipbuilding techniques more challenging, but (with the exception of change orders) no less rewarding. In fact, the increased level of outfitting should make the savings from zone outfitting even more significant than for merchant ships, although cable pulling will continue to be a hindrance for the foreseeable future. Zone hull construction is already being practiced by all naval shipbuilders, and the degree of zone outfitting is steadily improving. The hull block breakdown for the FFG-7 is shown in Figure 4.3.

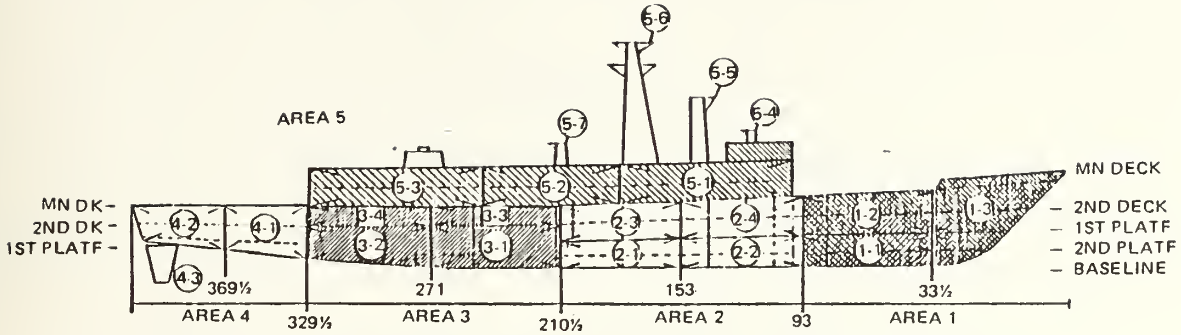


Figure 4.3. FFG-7 hull block breakdown.

CHAPTER 5

PIPING SYSTEM DESIGN AND FABRICATION

In Chapter 3, it was shown that shipboard piping systems are one of the major cost drivers in naval ship construction. While much emphasis has been placed on modern hull construction techniques in the last decade, similar attention is just now being given to modern outfitting techniques. Piping system work can be broadly classified into three categories: shop fabrication, installation, and system testing. On-board system testing (after complete installation) accounts for only about 6 percent of the pipe shop's manhours on any given system and will not receive further analysis here. The focus of this and ensuing chapters will be on shop fabrication, although installation is an inseparable consideration. Present manhour accounting methods make it difficult to compare the labor expenditures for fabrication versus installation. It is known that roughly one third of the piping system manhours on a moderately sized naval combatant ship is spent on assemblies that are installed prior to block erection on the ways. The other two-thirds (minus 6 percent for testing) are spent on assemblies that are installed on the ways or after launching. The breakdown of manhours between fabrication work and installation work, however, is very difficult to extract from available data.

This chapter will discuss piping system design requirements, naval shipboard piping systems, and pipe shop fabrication procedures. The next two chapters will apply modern industrial engineering techniques to piping assembly fabrication.

5.1 Piping System Design Requirements and Procedures

Piping system design follows the overall ship design procedure that was outlined in chapter three. The contract design plan includes major arrangement diagrams and system specifications (temperature, pressure, flow rate, etc.). System materials and sizes might or might not be specified by the contract design plan. The lead shipyard then makes the detailed pipe design plan by connecting the machinery in such a way that the system specifications are met. A modern shipyard will normally have a design division and production engineering division. Although the precise division of responsibilities between the two will vary from yard to yard, the following discussion properly delineates the procedures and thought processes involved in making the detailed design plan.

The design division selects the type and size of pipe and decides how it will run through the ship, as well as locating valves, strainers, and other functional components (if these weren't already specified by the contract plans).

In designing the system, the design division is guided by the system specifications and applicable milstandards. The actual path of the pipe will be based on arrangement considerations and the desire to minimize the amount of material used. The production engineering division then adds the fabrication components (couplings, elbows, tees, etc.) and decides how the system will be divided up into assemblies and subassemblies. Production engineering's objective is to incorporate producibility considerations, thereby minimizing labor hours and material costs involved in fabrication and installation. They might also recommend changes to the piping route, if necessary, to incorporate producibility features into the subassembly fabrication. The plans then go back to design for final approval. In the actual design process, there would be considerable interaction between design and production engineering, and the plans might go back and forth a number of times before reaching final approval. Pipe detailers then make the working plans which the shop uses

to actually do the work. Working diagrams for three FFG-7 class patrol frigate firemain and flushing system assemblies are included in Appendix A.

The producibility considerations taken by production engineering generally concern either subassembly boundaries or subassembly fabrication details. Subassembly boundaries are determined by taking into consideration subassembly size and weight, shipboard joint accessibility, shipboard fit-up tolerances, and overall ease of fabrication. As a rule, it is easier to fabricate in the shop than on the ship, so overall ease of fabrication will generally favor larger subassemblies, thereby leaving fewer joints to be made up on board or on block. Size and weight are limited, however, by installation considerations. For installation on board, each subassembly must be able to fit through the doors and hatches and should be light enough to be easily handled without rigging equipment. The limitations for on-block installation are not as strict, since accessibility into the space is much easier. Pre-outfitting is therefore more efficient not only for the outfitting installation, but also by allowing more shop fabrication. Given the general size constraints, the specific boundaries are located based on joint accessibility and tolerance fit up. Joint accessibility simply requires that joints which are designated to be made up on board/block must be accessible. This is particularly applicable to welded joints, since locating the joint too close to a bulkhead, pipe, or other interference would hinder a welder's ability to make a sound weld.

Piping system accuracy control is difficult since it interacts with structural accuracy control. It not only depends on distortions and deviations introduced during the pipe assembly fabrication, but also is subject to the deviations in structure and equipment location which interface with the piping systems. Consequently, significant allowance is made for fit-up problems during installation. Joints other than butt welds and flanges have some axial flexibility inherent in their design,

so they can be used to compensate for one-dimensional inaccuracies. Orienting boundary joints at right-angles gives fit-up flexibility in two dimensions. Another technique that allows for fit-up problems is the practice of specifying certain joints to be only tack welded prior to installation. Rather than helping the fit up, this technique merely minimizes the amount of rework necessary if fit up is not possible, since only a tack weld must be ground out and redone. It has the unfortunate effect of moving the welding of that joint, even for a successful fit up, from the shop to the ship or block. One shipyard building noncombatants estimated that as many as 15% of the joints leave the shop in the tack welded condition. Similar statistics on combatants were unavailable.

The second concern of production engineering is the fabrication details of each subassembly. Perhaps the primary consideration is that bends are preferable to elbows. From a production standpoint, one bend is much easier than two welds or brazes. From a design standpoint, bends are less disruptive of flow. From a material standpoint, elbows cost money. Whenever possible, therefore, the subassembly should be designed to accommodate a bend. Accordingly, multiple bends on the same pipe piece must be separated by a distance adequate to allow the bending machine to make both bends. That distance varies with pipe size and bend angle, but is on the order of a half foot for right angle bends in a two-inch pipe. If shipboard arrangement constraints don't permit the separation, elbows would have to be used. When fittings must be used, whether they be elbows, couplings, or whatever, every effort should be made to use standard fittings. Designing Y joints with unique angles, for instance, should be avoided. This is largely a function of the original pipe route and pipe selection made by the design division. Selection of standard pipe sizes and joint designs which can utilize standard fittings is important and must be done by the design division at the very start of the design process.

Pipe material selection is determined primarily by the nature of the fluid the pipe will be carrying, with corrosion resistance being the

material parameter of major interest. The flow rate, fluid temperature, and fluid pressure then determine the pipe size and fabrication procedures. The applicable military standard for piping fabrication welding and inspection is MIL-STD-278D (SHIPS), dated 26 January 1970. It defines four classes of piping based on temperature and pressure; these are listed in Table 5.1. P-3 is strictly brazed piping. The other classes are welded, but all four can also contain mechanical joints.

Table 5.1. Piping classes on naval ships.[79]

Class	Pressure (psi)/Temperature (°F)
P-1	$P \geq 300$ or $T \geq 650$
P-2	$P < 300$ and $T < 650$
P-3	any pressure, $T \leq 425$ (brazed pipe)
P-LT	$P > 50$ psi and $T < -20$

In addition to the pressure and temperature criteria, P-1 includes any piping used for conveying lethal gases or liquids. Halon is included in this category, but freon is not. P-LT is not used for any of the systems that will be discussed in this thesis, so it will not receive further attention. P-1, P-2, and P-3 piping are commonly found on all naval vessels. The welding and inspection requirements for P-1 piping are predictably the strictest and will be discussed in more detail later in this chapter.

Shipboard piping systems can generally be categorized as carrying salt water, fresh water, fuel oil, lube oil, hydraulic oil, compressed gas, or steam. Oil and steam systems are normally composed of ferrous materials, fresh water is copper, and salt water is copper nickel. Steam

systems, which are extensive on nuclear and boiler type ships, are almost nonexistent on the newer gas turbine ships. Table 5.2 lists the major shipyard-installed piping systems on the FFG-7 class of patrol frigates. Also listed are the fluid or fluids carried by each system, the primary piping materials used in each system, and the total length of piping in each system. The length is given in feet and includes all piping down to 0.25 inches ips. Some shipboard systems, such as missile hydraulics, are not included because the work was subcontracted. The total length of piping is 86,619 ft. Pipe length as a function of diameter is listed in Table 5.3 and shown graphically for groups of diameters in Figure 5-1. Statistical breakdown of naval piping system components such as valves and fittings are not readily available. Although the statistics have been gathered, the shipyards are reluctant to release them for proprietary reasons.

The pipe diameters listed in Table 5.3 and shown in Figure 5-1 are not the actual internal or external diameters, but rather the International Pipe Standard (IPS). Ferrous pipe sizes are normally classified by their IPS number (also commonly referred to as iron pipe size or nominal pipe size) and schedule number. Numerically, the schedule number is approximately equal to 1000 times the service pressure divided by the allowable stress. It is a measure of the wall thickness of the pipe.

$$\text{Schedule No.} \approx 1000 \times \frac{P}{S}$$

$$P = \text{service pressure (psi)}$$

$$S = \text{allowable stress (psi)}$$

Standard commercial steel pipes come in a variety of schedules from 5 to 160 and three other wall thickness designations: standard, extra strong, and extra-extra strong. Standard and extra stong are almost identical

Table 5.2. FFG-7 piping systems.(80)

System	Fluid(s)	Primary Material(s)	Total Pipe Length (ft)
AC and condensate drain	FW	Cu	6031
Refrigeration	FW	Cu	654
Magazine sprinkler	FW	Al	2056
Electronics cooling	FW	Cu, SS	3345
Potable water	FW	Cu	7561
Waste heat circulating	FW	Cu, CuNi	1111
Scupper and deck drains	FW, SW	Al	460
Plumbing drains	FW, SW	Cu, CuNi	9235
Distilling plant	FW, SW	CuNi	466
Drainage and ballast	FW, SW	CuNi, S	3112
Salt water cooling	SW	CuNi	2904
Firemain and flushing	SW	CuNi	4895
Water washdown	SW	CuNi, SS	2692
Waste/oily water	SW	CuNi	4729
Fuel oil service	FO	SS	592
Diesel generator fuel	FO	S	1365
Fuel fill and transfer	FO	S, SS	5960
JP-5	FO	CuNi	1305
Lube oil fill, transfer, purify	LO	S	2284
Propeller hydraulics	HO	S	373
Boat handling hydraulics	HO	SS	155
Fin stabilizer hydraulics	HO	SS	174
Gas turbine starting air	CG	SS	354
Control air	CG	Cu	4154
HP, LP air	CG	Cu, CuNi, SS	
Nitrogen	CG	Cu	119
Shore steam	steam	Cu	543
Diesel exhaust	exhaust	SS	367
Incinerator exhaust	exhaust	SS	43
Gauge piping	misc	SS, S, Cu	3843
Halon/AFFF	halon/foam	S, CuNi	6343
Voice tubes	---	Brass	81

Total: 86,619

FW = Fresh water
SW = Salt water
FO = Fuel oil
LO = Lube oil
HO = Hydraulic oil
CG = Compressed gas

Cu = Copper
CuNi = Copper-Nickel
Al = Aluminum
S = Steel
SS = Stainless steel

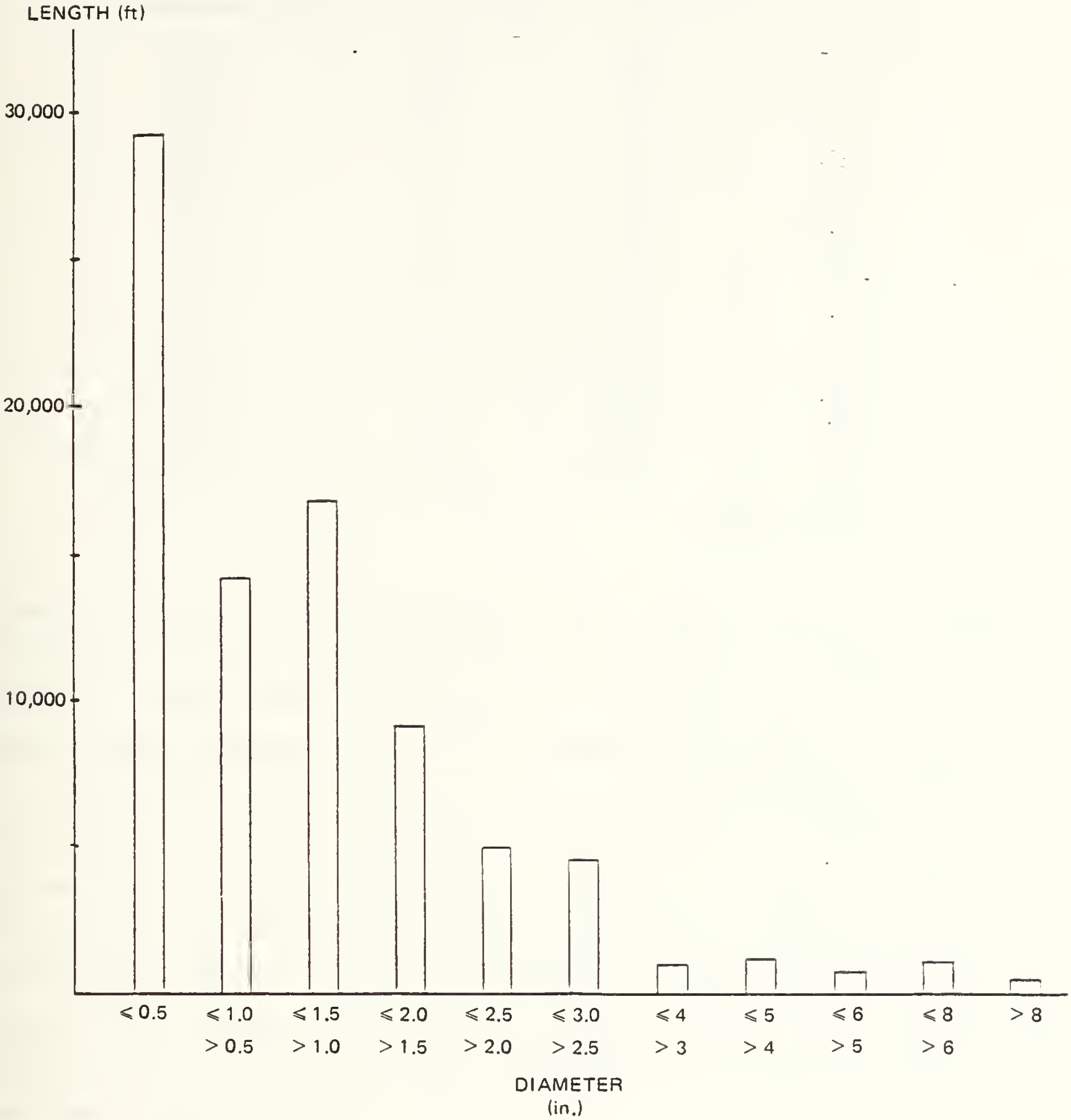


Figure 5-1. Total pipe length vs diameter on FFG-7.

Table 5.3. Pipe length vs diameter on FFG-7.

Diameter (in)	Length (ft)	Diameter	Length
0.125	421	2.500	4,937
0.250	13,729	2.625	12
0.375	5,089	3.000	4,515
0.500	9,904	3.125	37
0.625	45	3.500	92
0.750	7,359	3.625	47
0.875	116	4.00	4,696
1.000	6,563	5.00	1,123
1.125	119	5.50	10
1.250	7,364	6.00	730
1.320	506	6.60	10
1.375	75	8.00	1,018
1.500	8,651	10.00	113
1.700	545	14.00	136
2.000	8,465	16.00	192

Total: 86,619

to Schedule 40 and Schedule 80, respectively. Table 5.4 lists the wall thickness in inches for all the schedules of steel pipe commercially available. Sixteen inches is the largest pipe used on most naval ships. Schedule numbers followed by an "s" are commonly available in stainless steel. For pipes larger than 12 inch ips, the size designates the actual outer diameter of the pipe. Actual thickness may be as much as 12.5% below the nominal thickness due to mill tolerance. Copper and brass pipes use a similar designation scheme, but commonly come in only regular or extra strong rather than the wide range of schedules. A list of the outer and inner diameters for these is provided in Table 5.5. Strengths other than regular and extra strong are specified by wall thickness rather than schedule number.

It is obvious that a number of different codes and standards cover piping systems. The major commercial codes are the ASME Boiler and Pressure Vessel Code and the ASA Code for pressure piping. As previously mentioned, MIL-STD-278D (SHIPS) is the applicable military standard for pipe welding and inspection, and a number of additional military standards cover other aspects of piping systems, such as material selection.

Table 5.4. Wall thickness of ferrous pipe.(81)

Nominal pipe size	Outside diameter	Nominal wall thickness														
		Sch 5S	Sch 10S	Sch 10	Sch 20	Sch 30	Standard	Sch 40	Sch 60	Extra-strong	Sch 80	Sch 100	Sch 120	Sch 140	Sch 160	XX strong
1/8	0.405	....	0.049	....	....	....	*0.068*	0.068	....	*0.095*	0.095					
1/4	0.540	....	0.065	....	....	....	*0.088*	0.088	....	*0.119*	0.119					
3/8	0.675	....	0.065	....	....	....	*0.091*	0.091	....	*0.126*	0.126					
1/2	0.840	0.065	0.083	....	....	....	*0.109*	0.109	....	*0.147*	0.147	....	....	....	0.188	0.294
3/4	1.050	0.065	0.083	....	....	....	*0.113*	0.113	....	*0.154*	0.154	....	....	....	0.219	0.308
1	1.315	0.065	0.109	....	....	....	*0.133*	0.133	....	*0.179*	0.179	....	....	....	0.250	0.358
1¼	1.660	0.065	0.109	....	....	....	*0.140*	0.140	....	*0.191*	0.191	....	....	....	0.250	0.382
1½	1.900	0.065	0.109	....	....	....	*0.145*	0.145	....	*0.200*	0.200	....	....	....	0.281	0.400
2	2.375	0.065	0.109	....	....	....	*0.154*	0.154	....	*0.218*	0.218	....	....	....	0.344	0.436
2½	2.875	0.083	0.120	....	....	....	*0.203*	0.203	....	*0.276*	0.276	....	....	....	0.375	0.552
3	3.5	0.083	0.120	....	....	....	*0.216*	0.216	....	*0.300*	0.300	....	....	....	0.438	0.600
3½	4.0	0.083	0.120	....	....	....	*0.226*	0.226	....	*0.318*	0.318					
4	4.5	0.083	0.120	....	....	....	*0.237*	0.237	....	*0.337*	0.337	....	0.438	....	0.531	0.674
5	5.563	0.109	0.134	....	....	....	*0.258*	0.258	....	*0.375*	0.375	....	0.500	....	0.625	0.750
6	6.625	0.109	0.134	....	....	....	*0.280*	0.280	....	*0.432*	0.432	....	0.562	....	0.719	0.864
8	8.625	0.109	0.148	....	0.250	0.277	*0.322*	0.322	0.406	*0.500*	0.500	0.594	0.719	0.812	0.906	0.875
10	10.75	0.134	0.165	....	0.250	0.307	*0.365*	0.365	0.500	*0.500*	0.594	0.719	0.844	1.000	1.125	1.000
12	12.75	0.156	0.180	....	0.250	0.330	*0.375*	0.406	0.562	*0.500*	0.688	0.844	1.000	1.125	1.312	1.000
14 OD	14.0	0.156	0.188	0.250	0.312	0.375	0.375	0.438	0.594	0.500	0.750	0.938	1.094	1.250	1.406	
16 OD	16.0	0.165	0.188	0.250	0.312	0.375	0.375	0.500	0.656	0.500	0.844	1.031	1.219	1.438	1.594	
18 OD	18.0	0.165	0.188	0.250	0.312	0.438	0.375	0.562	0.750	0.500	0.938	1.156	1.375	1.562	1.781	
20 OD	20.0	0.188	0.218	0.250	0.375	0.500	0.375	0.594	0.812	0.500	1.031	1.281	1.500	1.750	1.969	
22 OD	22.0	0.188	0.218	0.250	0.375	0.500	0.375	....	0.875	0.500	1.125	1.375	1.625	1.875	2.125	
24 OD	24.0	0.218	0.250	0.250	0.375	0.562	0.375	0.688	0.969	0.500	1.218	1.531	1.812	2.062	2.344	
26 OD	26.0	....	....	0.312	0.500	....	0.375	....	....	0.500						
28 OD	28.0	....	....	0.312	0.500	0.625	0.375	....	....	0.500						
30 OD	30.0	0.250	0.312	0.312	0.500	0.625	0.375	....	....	0.500						
32 OD	32.0	....	....	0.312	0.500	0.625	0.375	0.688	....	0.500						
34 OD	34.0	....	....	0.312	0.500	0.625	0.375	0.688	....	0.500						
36 OD	36.0	....	....	0.312	0.500	0.625	0.375	0.750	....	0.500						
42 OD	42.0	....	....	....	....	....	0.375	....	....	0.500						

Table 5.5. Inside diameter of copper pipe.(82)

Standard pipe size, in.	Nominal dimensions, in.		
	Outside diameter	Inside diameter	Inside diameter
		Regular	Extra strong
1/8	0.405	0.281	0.205
1/4	0.540	0.376	0.294
3/8	0.675	0.495	0.421
1/2	0.840	0.626	0.542
3/4	1.050	0.822	0.736
1	1.315	1.063	0.951
1¼	1.660	1.368	1.272
1½	1.900	1.600	1.494
2	2.375	2.063	1.933
2½	2.875	2.501	2.315
3	3.500	3.062	2.892
3½	4.000	3.500	3.358
4	4.500	4.000	3.818
5	5.562	5.062	4.812
6	6.625	6.125	5.751
8	8.625	8.001	7.625
10	10.750	10.020	9.750
12	12.750	12.000	

5.2 Piping System Fabrication Processes

This section will describe the major operations that a pipe shop performs in the fabrication of piping assemblies.

(1) Cutting. Pipes are generally marked for cutting with a steel tape measure. Tolerances are not well-defined, although 1/8 inch seems to be the usual shop practice. Frequently pipe is left intentionally long with the idea that more can always be cut off later if necessary. Cutting is accomplished either with heat or mechanically. The simplest heat method is an oxy-acetylenc torch; the torch is held stationary while the pipe rotates. The torch can also be angled to give the end of the pipe an appropriate bevel, although it must still be further machined or ground. Generally 1/8 inch cutting allowance is added to the marked length of a pipe that will be flame cut. Plasma cutting is the other major heat method and is identical except that uses a plasma arc rather than a flame. Mechanical cutting methods include band saws, rotary blade saws, and hand-held cutters. The hand-held cutters are essentially just c-clamps with a rotary blade, similar to a can opener blade, and come in a wide range of sizes capable of cutting copper pipe up to six inches in diameter. At one yard, all copper pipe less than three feet in length is cut by hand; longer lengths are cut on a saw. Saws must be followed by machining or grinding if a bevel is required for end prep. Some yards do beveling on a machine that works very much like a pencil sharpener; other yards do almost all beveling by hand grinding. The inside of the pipe must also be cleaned up after burning or cutting, either using a reamer or hand file to remove metal and debris. One yard is installing "clamshell" cutters that make

the cut with no length allowance required and bevel both sides of the cut.

(2) Bending. Although modern fabrication techniques favor delaying bending until later in the fabrication process, bending generally follows immediately after cutting and beveling. Bending can be done either hot or cold, but almost all bending done in a shipyard for surface ship construction is cold bending. Pipes in excess of a 10-inch diameter are generally hot bent, but shipyards usually use elbows for anything above 8 inches. Hot bending involves filling the pipe with sand (to minimize thinning and ovality) and heating the pipe to 1900°F (for ferrous materials). The pipe is then placed on a pin table where it is forced into the desired shape and allowed to cool. Cold bending is much faster and is therefore the method of choice if the shipyard has the proper equipment. Rotary-type bending machines are commonly used in all shipyards for cold bending pipe up to 8 inches in diameter. Cold bending larger pipe is possible (and is commonly done up to 12 inches in diameter in Europe), but the small amount of work on pipe that large in naval shipbuilding has made it economically undesirable to invest in rotary benders that large. Rotary benders form the pipe around a circular die while the inside of the pipe is supported by a mandrel. A short section of pipe (about four inches for a two-inch pipe) immediately downstream of the die is held firmly by a clamp lock and is forced around with the die as the die rotates to make the bend. The clamp lock is one aspect of current bending machine design that necessitates a finite distance between bends on the same pipe.

Mandrels come in a variety of designs, as shown in Figure 5-2. The mandrel must fit snugly; consequently, a different sized mandrel is required not only for each

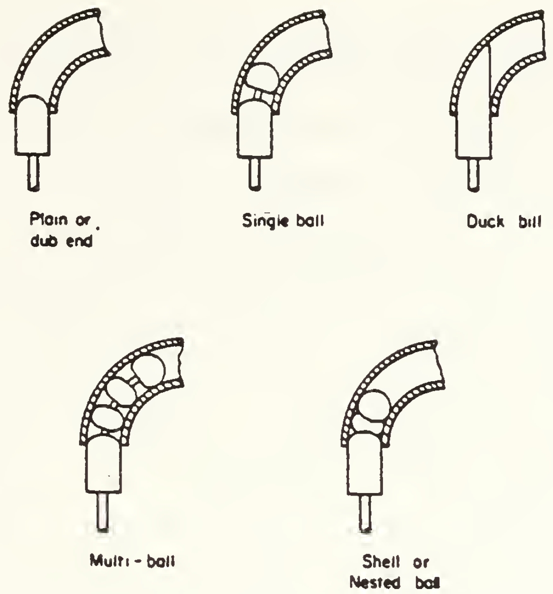


Figure 5-2. Different mandrels for pipe bending.[83]

standard pipe diameter, but also for each wall thickness at each diameter. Outer diameter is the only pipe dimension that matters for the die. Dies are available for all standard pipe sizes and a range of bend radii. Five pipe diameters is the most common commercial bend radius, although three diameters is very common in naval piping systems. Radii as small as two pipe diameters are produced by some shipyard benders. Ferrous pipe must be normalized after a 2-D bend; copper, copper-nickel, and aluminum pipe should be annealed prior to bending. The bending machine operator uses his experience and judgement to determine how much to overbend the pipe in order to compensate for springback. Several yards have automated pipe benders with programmed advance, bend angle, and roll angle. There is no automatic compensation for springback in these machines; the operator has to input a slightly larger bend angle than desired.

Figure 6-3. Differrent ...

standard pipe diameters, ...
each diameter. Once the ...
then markers for ... ind ...
and pipe sizes and ...
there is the most ...
these diameters, it ...
Radii as small as ...
snipped sections ...
3-D bend, repeat, ...
extended prior ... bending ...
die experience all ...
bend the pipe in order ...
rators have ... that ...
bend angle, and pull length. ...
tion for springback is ...
input a slightly larger bend angle than the ...

The mandrels of rotary benders are oiled to allow free slippage along the inner pipe surface. Immediately after bending, the oil is removed from the inside of the pipe by dipping it in a caustic solution, then rinsing in hot water.

(3) Fit up. The first stage of assembly is fit up, during which all the components are brought into correct position and alignment, then held in place by tack welds or clamps. Almost without exception, fit up is done manually, without the aid of jigs or fixtures. Small components are fit up entirely by hand by one or two workers, while larger components might require the use of a vise or chainfall. The Piping Handbook outlines the normal commercial procedure:

> In making up subassemblies, the usual procedure is to set up the largest component, either on adjustable support "horses" or on a level-top "layout" table, with its longitudinal axis in a horizontal plane. The longitudinal axis and one end of the member are then used as baselines to which the locating dimensions and setting of the smaller parts can be referred, using a rule, steel tape, hand level, squares, straightedge, or bevel protractor as required.
>
> Normally, in shop fabrication, an end-to-end tolerance of ±1/8 inch is considered the maximum that is acceptable. However, more rigid tolerances may sometimes apply to specific piping components.(84)

No adjustable supports were observed being used for fit up in any of the shipyards the author visited. The alignment of large components in at least one yard is routinely done with chainfalls, ropes, and wooden blocks and wedges. In the particular case observed, the workers were having a fair amount of difficulty bringing all the pieces into proper alignment, but the supervisor claimed that minor differences between the same assembly in two ships of the same class make fixtures uneconomical. Regardless of how it is accomplished, accurate fit up is critical, since poorly done fit ups are a major cause of weld defects. Weld shrinkage is generally negligible in socket and fillet welds, but longitudinal shrinkage in butt welds is a factor and allowance should be made for it during fit up. For Schedule 40 and Schedule 80 carbon or low-alloy steel piping, shrinkage is typically one-half the root spacing after tack welding.(85)

Small and moderate sized fit ups are accomplished either by a pipefitter or a pipefitter and a welder. Shipyard pipe shops generally have a separate area designated for fit up, then move the tack-welded assembly to the welding area for production welding. Brazed pipe also has a separate fit-up area, where the pipe ends are sanded, flux is applied, and the joints are assembled. For assemblies with many brazed joints, the joints are fit up and brazed sequentially, either individually or in groups of two (or three at most). For example, two joints would be fit up, then the assembly would be taken to the brazing station for brazing, then taken back to the fit-up area where the next one or two joints would be fit up. Fitting up all the joints at once, then brazing them all, is not currently considered practical because the joints do not hold themselves together (as tack-welded joints do). Clamps would have to be used, and unless special clamps were

designed for the purpose, they could interfere with securing and brazing of assemblies with multiple joints in close proximity.

For both brazing and welding, the actual physical fit up is either preceded by or includes any remaining end preparation that needs to be done. Bevels might be made during or immediately after cutting, but last minute cleaning or grinding of the pipe end is frequently required. In some cases, beveling is delayed until fit up or adjusted during fit up to obtain the proper root spacing. In still other cases, excess pipe was included during cutting, and the excess must be removed during fit up. Statistics on the frequency of each type of fit-up problem were unavailable, but it appears to be a fertile area for formal accuracy control analysis.

(4) Welding/Brazing. Shipyards routinely employ shielded metal arc (stick), gas tungsten arc (GTA), and gas metal arc (GMA) welding, although the frequency of use of each varies greatly from yard to yard. Stick welding is generally used only on carbon steel pipe, but it is seldom if ever used on the root pass. GTA welding, more commonly referred to as TIG (tungsten inert gas), is used on the root pass of most steel piping, since it does not run the risk of drop through that stick welding does. Drop through is a condition of excessive penetration in which the molten metal from the weld pool enters the pipe interior and solidifies, forming an irregular surface. It is particularly important to avoid drop through in lube oil systems, where a solidified globule of weld metal could conceivably survive the system flush, then break off during later service, causing considerable equipment damage (or at least considerable excitement, if found in a lube oil filter). Stainless steel pipe is generally welded with GTA

for the first two passes, then GMA for the remainder of the weld. GMA is also used for welding aluminum pipe. Copper-nickel can be either welded with GMA or brazed, although the trend is away from brazing. Heli-arc is a process very similar to GMA; the distinction is that heli-arc welding melts a puddle, then feeds the wire into the molten puddle, whereas GMA melts the puddle and the wire, and the molten wire either sprays or drops into the puddle. Heli-arc generally gives a smoother finish and spatters less; it can be used in any application currently being done by GMA.

Some shipyards are moving toward automated or semi-automated welding procedures. In a typical semi-automated welding apparatus, the pipe is set in a holding device that rotates the pipe while the welding torch remains stationary. The pipe is held in place by three or more radial clamps, much as a drill bit is held in place by the chuck of the drill. The equipment can generally handle only straight pipe pieces; therefore, welding should be done prior to bending on assemblies containing both bends and welds. Post weld heat treatment is required on certain alloy steels, such as the chrome molybdenum steel used in main steam systems. On the gas turbine ships currently being built, though, there are no pipes requiring post weld heat treatment.

Brazing is used on all copper pipe and some copper alloys. Most brazing is done by flame; induction brazing is not approved for use on most naval systems. Brazing is done at a large table outfitted with suction ventilators and vises for holding the pipes while brazing. Rotating pedestals are frequently used for short pieces that are stable vertically. The workpiece stands on the pedestal and rotates, thereby freeing the brazer from having to move the torch around the joint.

(5) Testing and inspection. Completed joints and assemblies can be tested by a number of methods. Nondestructive testing (NDT) includes radiography testing (RT), magnetic particle testing (MT), liquid penetrant testing (PT), ultrasonic testing (UT), and eddy current testing (ET). These tests are performed according to the procedures outlined in MIL-STD-271. Visual inspection and hydrostatic testing complete the list of available quality assurance methods. Visual inspection checks the soundness of the weld or braze and is done either formally or informally on every joint. RT uses X-rays to detect weld root defects and internal discontinuities in the weld or base metal. MT exploits the change in magnetic field that results from near surface discontinuities such as cracks, seams, laminations, porosity, and lack of fusion or penetration. A large current is passed through the weld, and iron particles are sprinkled on the surface to detect the magnetic flux lines and possible disruptions due to weld defects. MT can be used only on ferromagnetic materials. PT checks for surface defects with a dye that penetrates into those defects, then is brought back to the visible surface by a "developer." The developer is sprayed onto the surface after the dye has been applied and wiped away from all smooth surface areas. UT sends ultrasonic waves into the metal, and locates defects by their reflection of those waves. UT can also be used to check wall thickness, since the time of return for the waves is proportional to the distance to the reflection boundary (which in this case would be the pipe inner wall). In naval piping systems, UT is used almost exclusively to check for adequate bonding in brazed joints. ET, like MT, detects defects by the changes they create in magnetic fields. However, in ET an applied primary magnetic field induces eddy current in the pipe, which in turn induces a secondary magnetic field that shows the disruptions due to

defects. ET is used almost exclusively to detect defects in heat exchanger tube bundles, since the primary magnetic field can be applied by an internal probe that is pushed through the pipes. Hydrostatic testing can either be done on each pipe assembly in the shop (if joints in the assembly require it) or on larger sections of the system after shipboard installation. Welds must be strength tested by bringing the pressure up to as much as 150% of the system design pressure. After all welds have been verified, the entire system must be tested for tightness of mechanical joints at the system design pressure. All further use of the term "hydrostatic test" in this thesis will refer to the weld strength test.

The requirements for applying each test are specified in MIL-STD-278d (SHIPS). Table 5.6 summarizes the NDT requirements for P-1 and P-2 piping. P-3 piping (brazed) is covered by NAVSHIPS 0900-001-7000, which requires UT inspection of certain critical joints. The testing requirements for P-LT piping are generally the same as those for P-1 piping. There are a number of exceptions to Table 5.6, and they are generally specified on the drawings.

(6) Surface treatment. Post weld surface treatments include cleaning, painting, and galvanizing. Brazed pipe must always be dipped in acid after brazing in order to remove the flux. Steel pipes requiring post weld cleaning are also soaked briefly in acid, a process referred to as pickling. Sulfuric, hydrochloric, or phosphoric acid is the cleaning agent, and an inhibitor is added to minimize attack on the metal. The process is concluded by adequate rinsing in hot water (above 140°F). Another common cleaning process is the caustic solution dip that is used for removing the bending

Table 5.6. Welded pipe joint inspection requirements.[86]

			Visual Inspection		MT/PT Test				
Pipe Class	Joint Type	Pipe Size (IPS)	In Process	Completed Weld	In Process	Completed Weld	RT of Completed Weld	Extent of RT	Hydrostatic
P-1	butt	≥ 4	X	X	X	X (1)	X	360°	X
	butt	2.5-4	X	X	X	X (1)	X	$\geq 60°$	X
	butt	<2.5	X	X	X	X (1)	X (2)	$\geq 60°$	X
	socket/fillet	all	X	X	X	X			X
P-2	butt	≥ 2.5		X		X			X
	butt	<2.5		X					X
	Socket/fillet	all		X					X

(1) MT/PT shall be performed only when post weld heat treatment is required and shall be done after heat treatment. When 360° RT is to be performed, MT/PT may be omitted.

(2) RT is only required if working pressure exceeds 575 psi. For 575 psi and below, MT or PT is sufficient.

oil. At least one major shipyard does not have pickling facilities and uses the caustic solution not only for oil removal, but also for final cleaning when necessary. If surface oxides must be removed, that is done with shot blasting prior to fabrication. Acid dip is used only for flux removal after brazing. Assemblies that absolutely must be pickled are sent to a vendor. Other shipyards have their own pickling tanks. Cleaning requirements are a function of the shipboard system into which the assembly will be installed. In general, P-1 piping and oil system assemblies must be cleaned prior to installation. Completed assemblies which include functional

components such as values, however, are not dipped in cleaning solutions. In such cases, the pipe would be thoroughly cleaned before fabrication, then, if system cleanliness requirements necessitated it, the completed assembly would be flushed prior to installation.

Painting is done in the shipyard, but outside of the pipe shop. Assemblies which require painting are fabricated a few days earlier to allow time for it, but there is no direct pipe shop involvement. Galvanizing in most shipyards is subcontracted to a vendor. The completed pipe assembly is shipped to the vendor and returned in a normal time frame of two weeks. Galvanizing, however, is rarely done.

(7) Other processes. Two other processes, threading and drilling, are performed on piping assemblies on an occasional basis. Threading is done to some aluminum and brass pipes when low pressure union joints are called for. Drilling is performed when a small branch is desired without a tee fitting. Both threading and drilling are simple operations that require only minimal setup time.

(8) Final assembly. In addition to welded and brazed joints, many assemblies leave the shop with mechanical joints (primarily flanges). In copper assemblies, these would almost always be made up after all brazing is completed. In welded assemblies, the mechanical joints are frequently made up prior to welding, particularly if the mechanical joint spacing influences the welded joint fit up.

During the entire fabrication process, the majority of transport within the shop is done by hand. Most assemblies are light enough to be carried by the worker to the next workstation. Heavier assemblies (which are predominantly ferrous) are transported on a pallet by forklift. Numerous cranes are also available in most pipe shops for transporting or positioning, as required.

CHAPTER 6

PIPE CODING AND CLASSIFICATION SCHEME

The fundamentals of group technology were outlined in Chapter 4. The objective of this chapter is to examine the possible applications of group technology to piping system fabrication, select the desired applications, and develop a coding and classification scheme for those applications. Existing schemes will also be analyzed.

6.1 Group Technology Applications to Piping

The application of GT to piping system fabrication is not unlike its application to other manufactured items in that the objectives can be classified into five major areas:

(1) Design recall

(2) Development of manufacturing cells

(3) Computer-aided process planning

(4) Workload balancing

(5) Work content estimating

Two other areas that do not fit within the strictest definitions of group technology but which could be useful outputs of coding schemes are:

(1) Material requirements list

(2) Accounting/scheduling

6.1.1 Design Recall

Even a modestly sized naval combatant has over 10,000 pipe assemblies. It is undoubtedly true that many of these assemblies either are or could be very similar in design. Furthermore, if all of the subassemblies were considered separately from their respective assemblies, it is possible that many would be identical. For the sake of clarity, an assembly will be defined here to mean any fabricated group of pipes, valves, fittings, and other components that is to be installed on-board, on-block, or on-unit without further fabrication. It could be as simple as a single piece of straight pipe or extremely complicated, with many pipes and components arranged in a complex configuration. A subassembly is simply a building block of a more complicated assembly. The distinction is somewhat grey and depends only on whether or not it will be installed as is, without further fabrication. Although "assembly" implies some degree of complexity, a simple assembly could involve less work than the subassemblies of a more complex assembly.

Piping assemblies are basically designed individually and from scratch, with the designer's personal experience providing the only means of design recall and standardization. In some cases shipyard practice has led to the development of standard designs for similar shipboard configurations, but there is not a systematic method for identifying all the similar configurations that exist on ships. It is probable that many of the assemblies could be adapted from an existing design used elsewhere in the ship or even in a previous class of ships. Finding a similar existing design, however, would be an enormous task under current design procedures. A coding scheme that adequately described the form, fit, and function of piping assemblies would allow the designer to quickly and easily locate similar existing assemblies. However, piping assemblies, unlike machined parts, can grow like ten-headed beasts. To adequately describe the form, fit, and function of an assembly with several valves, several flanges, and branches coming off at various angles would be beyond the capacity of a reasonably sized coding scheme. Design recall,

therefore, might be feasible only for subassemblies and simple assemblies. Shipboard piping systems must be routed in rather unique paths because of arrangement constraints, and assemblies reflect this in their complexity. Previously designed subassemblies (or simple assemblies), however, could be joined together to make complex and very unique assemblies.

6.1.2 Development of Manufacturing Cells

This application actually embodies a number of coding and classification uses. It is the culmination of a series of manufacturing applications based on grouping the assemblies into families of similar fabrication requirements. In its simplest form, GT can be used to form families based on equipment setup requirements, then manufacture family members as a batch. Similar operations are thereby performed together, and time is not wasted in switching from one operation with one setup to another operation with a different setup, then back again to the original operation. Reduction in setup time, therefore, is the most fundamental goal of work cell development, and it is achieved merely by sequencing (or batching) the shop work so as to manufacture family members together. If similar assemblies are to be manufactured using the same equipment setup, then it also makes sense to use the same workers, who thereby specialize in that family and benefit from the learning curve. The next level of advancement is the development of jigs and fixtures for a particular family. These "permanent setups" become economically advantageous when sufficient products are identified as being in the same family. This implies, of course, that fixture requirements are identified in the code and used as a basis for family groupings. The final level of advancement is the development of the work cells themselves. If production volume is sufficient to justify it, then groups of machines can be dedicated to manufacturing only certain families of products. All the machines, jigs, and fixtures dedicated to the manufacture of a particular product family can be located physically together to form a physical work

cell. If the dedicated equipment maintains its position in a functional shop layout, then it is a virtual work cell. A physical cell has the advantage of less transport time. "Process flow lane" is a phrase used interchangeably with work cell, although the former implies a physical arrangement that is spread out in a somewhat linear fashion rather than clustered together.

While none of these applications (batching, specialization, fixturing, and cell development) is necessarily dependent on the formal development of a GT coding and classification scheme, a code can provide a very convenient and thorough means of identifying product families. And while all shops practice these applications to some degree, GT classification families provide the basis for the introduction of rigorous economic analysis into shop operations. For example, sequencing all work of a given nature into a given time frame will certainly reduce setup time, but it will increase in-process inventory since it may require work on some assemblies to be done well ahead of the installation schedule. Balancing competing objectives in a manner that optimizes the overall shop operation requires more than the gut feel of the shop head; it requires a formal analysis for which GT can provide the basis. Family grouping into work cells is another economic issue. For shops producing a low volume of dissimilar products, the family sizes might be too small to justify any work cells. Even for large volumes of similar products, certain families will remain outside the product range covered by work cells. A typical shop performance curve as a function of the number of work cells might look like that shown in Figure 6-1. The exact shape of the curve will vary with product family breakdown, output volume, and cell design, and should be determined by rigorous analysis.

In applying all of this to piping fabrication, a good place to start is with the identification of pipe shop equipment setup times. The following discussion is based on equipment currently in use or being procured for use in several shipyards visited by the author. Recall from Chapter 5 that the major pipe shop operations are cutting, bending, fit

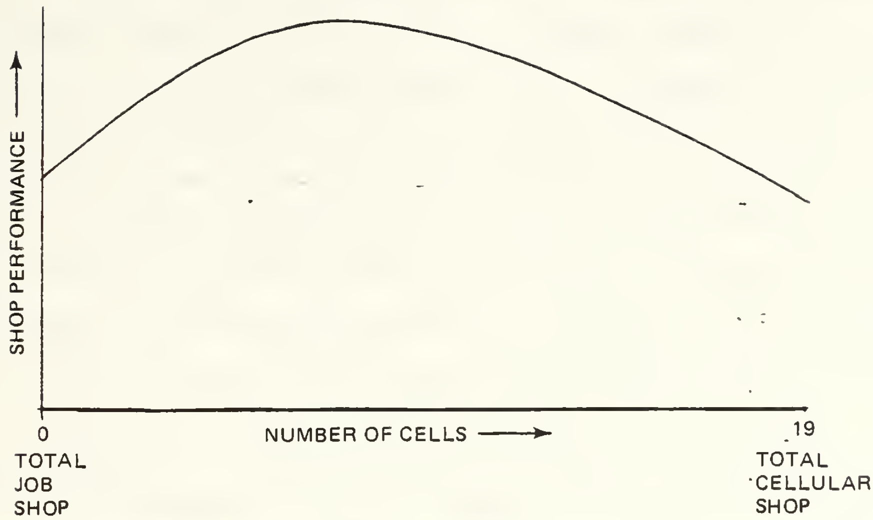


Figure 6.1. Effect of work cells on shop performance.[87]

up, welding, brazing, cleaning, inspecting, drilling, threading, and final assembly. Of these, only bending has a significant setup time. Equipment setup time for cutting on most modern cutting machines is negligible and unaffected by pipe diameter, wall thickness, material, or cut length. Frequently, however, shop practice is to use different cutters for different diameters of pipe, since a small saw would have difficulty cutting a 6-inch steel pipe. There is generally one cutter dedicated to large pipes (such as four inches and above), and several cutters used for smaller pipes. The fit up process can be slow and tedious, but there is no equipment setup time involved. It's all done by hand. Tolerances are achieved by the use of rulers, protractors, and level indicators. The only exception to this is in end preparation, for which a grinder or beveling machine might be used. Grinders require no setup time, and their use is independent of pipe attributes. Beveling machines, however, do use a different machining head for each diameter. At least one yard also uses a different bevel angle when the weld joint will require NDT. While making the appropriate adjustments to the equipment is not difficult, there is a slight amount of setup time involved.

The actual welding requires almost no setup time if done manually. For semi-automated welding, there is a small setup time for securing the workpiece in the rotational device, but the setup is essentially independent of the workpiece attributes. Many workpieces cannot be welded in this manner because of their configuration, but for those that can be, the setup is the same regardless of diameter, wall thickness, etc. For different materials, the wire spool and possibly even the shielding gas must be changed, but these take a matter of seconds. Fully automated welding on the other hand, could have a significant setup time, particularly if the welding robot employed a teach mode. Although such systems are used for structural work in a growing number of shipyards, none that are known of are currently used for piping nor will be in the foreseeable future. Brazing is all done manually and requires virtually no setup time. Cleaning consists of either dipping in a cleaning solution (caustic or acid) or shot blasting. In either case, setup time is negligible and independent of product attributes. The requirements for cleaning, on the other hand, are very product dependent, but this will be covered by process planning. This is also the case for inspection. Drilling and threading require minimal setup time, and the setup that is required is essentially independent of product attributes. These are also rare operations. Final assembly, during which all mechanical joints are put together, is all done manually with virtually no setup time.

Bending, as previously mentioned, does have a significant setup time, and it is due to the time required to change the die, clamp lock, and mandrel. The die and clamp lock are sized by the outside diameter of the pipe, and the die also varies with desired bend radius. To identify all the pipe requiring a particular die and clamp lock setup, therefore, would require grouping into families by nominal pipe size (outer diameter) and bend radius. Mandrel selection is also influenced by wall thickness. A family that would use the same bender setup would therefore have to have outer diameter, bend radius, and wall thickness. Since wall thickness is also a function of material, all family members might also

be of the same material. This would make family sizes very small, so it is questionable whether mandrel size should be included as a family attribute. Additionally, changing mandrels is much quicker than changing dies. All but the largest mandrels take only a few minutes to change, whereas die changeover times are much longer, as listed in Table 6.1. To shift from a four-inch to a five-inch die would require 10-minute removal time plus 35-minute installation time for a setup of 45 minutes (not including changing the mandrel or positioning the pipe). Actual process time for any right angle bend is only about 30 seconds.

Table 6.1. Bending machine setup times.[88]

Die Size	Die/Clamp Installation	Die/Clamp Removal	Mandrel Changeover
3/4 - 1-1/2	4	2	2
2 - 3	10	5	3
3-1/2 - 4	20	10	5
5 - 6	35	15	7
8 (in)	45 (min)	20 (min)	10 (min)

Table 6.2 qualitatively summarizes the setup times for each shop operation (as presently performed) and the product attributes which would have to be identified in order to uniquely specify the required equipment setup. Selection of which of these product attributes will be used in the code will be discussed later, based not only on setup time, but on other applications as well.

Fixturing is the next level of GT application to work cell development. Currently, almost no jigs or fixtures are used in pipe fabrication. Semi-automated welding is the one possible exception to this, since it utilizes some simple, adjustable fixtures (Y-supports) to aid in workpiece rotation. Fixtures could have some application in fit up, which is currently done entirely by hand using vises, chainfalls, blocks,

Table 6.2. Pipe shop setup times.

Operation	Setup time	Product Attributes
Cutting	Negligible	Unaffected
Bending		
Die/clamp	Significant	Diameter, bend radius
Mandrel	Moderate	Diameter, wall thickness
Fit up	Minor	Diameter, NDT requirements
Welding	Negligible	Unaffected
Brazing	None	--
Cleaning	Negligible	Unaffected
Inspecting	Negligible	Unaffected
Drilling	Minor	Unaffected
Threading	Minor	Unaffected
Final assembly	None	--

and wedges. The critical parameter for fit up are lateral and angular alignment, end preparation, and root spacing (for butt welds). For small to moderately sized assemblies, manual fit up works fairly well. For very large assemblies (where the wedges and chainfalls are required), fixtures could significantly facilitate fit up. The critical attribute for a family that could utilize common fixturing would be configuration. The geometric shape of the assemblies or subassemblies would have to be similar. As discussed in design recall, configuration can be very difficult to code, although key aspects of it might be identifiable.

In order to actually design work cells, all the attributes that determine equipment selection would have to be identified. Process and setup time for each operation would also have to be contained within the code. This is closely related to process route generation, the subject of the next section.

6.1.3 Process Route Generation

Also called computer-aided process planning (CAPP), process route generation utilizes the software program to generate process plans based

on information about the end product. With a variant-based planning scheme, the product information is contained within the code. The code identifies the assembly as belonging to some particular family for which a predetermined process route has already been established. A generative planning scheme, on the other hand, obtains a product description either from the code or from some other means (such as an interactive terminal session), then uses artificial intelligence to make up a process plan. The primary advantage of CAPP is the standardization of process plans. As presently done in most industries, several planners could make very different process plans for very similar parts. One nonshipbuilding company reportedly "used 51 machine tools and 87 different process plans to produce 150 parts. An investigation determined that these parts could be produced on only 8 machines via 31 process plans."(89) Just as design recall reduces new part proliferation, CAPP reduces process plan proliferation.

In a shipyard pipe shop, the term "process plan" implies a bit of formality that simply doesn't exist at the present time. Assembly fabrication is done according to the detailed sketch, but the lead pipefitter for that assembly uses his experience and judgement to determine the process sequence on a case-by-case basis. While he undoubtedly comes up with a good sequence, it might not be the best possible sequence, and there is no uniformity in sequencing. For example, suppose a worker is given a copper assembly to fabricate with the pieces of pipe, one bend, and four brazed fittings. He'll certainly cut the pipe pieces first, then make the bend, then start fitting up the joints. He might fit up one joint, have it brazed, then fit up the next two, and so on. Or he could fit up three of the joints to begin with. He might even delay bending until after completion of brazing. If he fits up too many at one time, the brazer might have trouble brazing one joint without the others shifting or coming apart. The exact sequence is a function of experience, judgement, and personal preference. The reason for this wide

discretion is the uniqueness of most of the piping assemblies. Two important questions must therefore be answered if GT is to be used for CAPP for piping assemblies. First, does the degree of assembly uniqueness really justify the absence of standardized process plans? Second, would standardized process plans really be that advantageous? In other words, does it really matter whether joints are fit up, then brazed individually or in groups of two? The answer to the second question is probably no for a completely manual shop. However, if pipe shops are to ever automate, then the answer is clearly yes. That is already occurring to some degree with semi-automatic welders, which can be used much more easily if the pipe has not yet been bent. The answer to the first question is probably no, the uniqueness is not sufficient to justify the lack of standardization. While there will always be some very complex assemblies that defy standardization of any kind, the majority of assemblies have enough similarities that a reasonable number of process plans could be made up to sequence their work. It would be a tedious task, and most shipyards have probably not attempted it because the benefits are not immediately obvious. To incorporate adequate information in the code to generate process plans would require coding all of the operations that were to be done to the assembly, and coding configuration information that would determine the exact sequence of operations. If the extent of work in each operation were also known, then the theoretical through-put time could be calculated.

6.1.4 Workload Balancing

Workload balancing is a means of controlling work in progress to maintain a steady, even flow through the shop. Periods of slack are eliminated, as are bottlenecks, by regulating the distribution of work within the shop. While schedule float time gives the shop planners some flexibility in adjusting shop workload, it does not provide a rigorous method for balancing the workload so that all personnel and work stations are fully utilized but not overburdened.

In a typical shipyard pipe shop, shop planners (or assistant foremen) make up a shop fabrication schedule based on the ship construction schedule produced by the shipyard planners. The ship construction schedule specifies when certain segments of system installation are to be complete on board or on block. The shop uses that to determine when each assembly must be ready for installation, and works backwards to come up with the fabrication schedule. The shop schedule starts things moving 11 weeks before the finished assembly will be needed for installation on board. In the first week, the material list is given to the shop stock room to have a material order written, and the stock room gives the order back to the planner. Four weeks are then allocated for the planner to send the order to the shipyard supply department, receive the material, and sort it by work order. At the end of five weeks, therefore, all material is on hand and the job is ready to begin. Three weeks are allowed to actually do the work, and there is a three-week buffer zone prior to the assembly actually being needed for installation.

Three weeks is much more time than is necessary to perform the actual work, so there is shop floor flexibility built into this system. The buffer zone adds additional flexibility, but necessarily creates in-process inventory that might be excessive. Furthermore, the fabrication schedule is based solely on the installation schedule. Since it is independent of assembly work content, bottlenecks at critical work stations can only be compensated for after they occur and are discovered. Likewise, work shortages at other stations can only be compensated for after discovery, at which point the material for the assemblies that could fill the work void might not be on hand. Thus, although this system is based on considerable experience and generally works adequately, it does not optimize shop operations and it does not prevent work disruption--it only reacts to it.

Workload balancing can prevent disruption by identifying workload requirements for each assembly, then scheduling the appropriate mix of assemblies so that all work stations are fairly evenly loaded. If it is

not possible to balance the workload due to the work content of the assemblies as a whole, then the capacity of the shop work stations should be appropriately adjusted, or subcontracting should be utilized to change the shop's workload. There is an implicit trade-off in this analysis between balancing and in-process inventory. If the shop would have to reach ahead three months in the schedule to get an assembly that would balance the workload, it might not be worth it. That decision will depend on many factors such as available laydown area and special material requirements.

In order to be useful for workload balancing, the GT code would have to specify not only the work stations that the assembly would need to go through, but also provide information upon which time estimates could be based.

6.1.5 Work Content Estimating

It was clear in the last section that work content must be identified in order to permit effective workload balancing. While time at each work station is the critical parameter for workload balancing, the quantitative nature of the work (independent of any time scale) might be of interest in and of itself. If, for example, the shop was considering purchasing a new bending machine and was trying to decide how large a machine to get, it would be very helpful to know how many bends of each pipe size the shop actually does. Such information is also necessary in designing process flow lanes, and it could be included in the code. To fully describe the work content would require identifying many assembly attributes, including the following: number and diameter of cuts; number, diameter, and bend radius of bends; material; number, diameter, and type of welds; number and diameter of brazes; drilling and threading requirements; final assembly requirements; inspection requirements; and surface treatment requirements. This is a rather formidable list of attributes, and it might be desirable to choose only the attributes for a more limited number of critical operations.

That completes the design and manufacturing applications of group technology to piping systems; however, material and accounting/scheduling are of practical interest to any shipyard coding scheme and will be discussed briefly.

6.1.6 Material Requirements List

Just as work content can be codified for each assembly, so too can material content. The information could then be used both for material ordering to support shop operations and as a basis for large-scale material content studies. The information that would have to be contained in the code would include pipe material, length, diameter, and wall thickness, fitting identification and quantity, and other component identification and quantity.

6.1.7 Accounting and Scheduling

In addition to a physical description of each assembly, a functioning shipyard needs to know how and when each assembly is to be used in the end product. Scheduling information is, of course, just dates. Useful accounting information would include the ship that the assembly is destined for, the unit on the ship into which it will be installed, the pallet of assemblies with which it will go to the ship, the SWBS system identification, and a piece or drawing number that uniquely identifies that assembly. All shipyards have their own systems currently in use to identify some or all of this information, usually requiring about ten total digits.

To summarize, code applications could be broadly categorized as design, manufacturing, material, or accounting/scheduling. Manufacturing would include cell development, generative process planning, workload balancing, and work content estimating. The pipe assembly attributes that would need to be identified in the code for each of these four categories are summarized in Table 6.3. Some of these attributes could be described by one digit; others would take a large number of digits. For

example, configuration would be very difficult to describe for all but the simplest of shapes. Fitting and component identification would also be very difficult. To fully identify a flange, for example, the code would have to specify, as a minimum, material, diameter, thickness, number of holes, hole diameter, and hole location. Method of casting or forging, certification standards, and mating surface finish would have to be known if it were to be used in certain critical systems. Valves would require even more information. Other attributes, such as bend radius and inspection requirements, could each be coded with one digit. The four major categories listed in Table 6.3 will next be briefly summarized.

Table 6.3. Pipe assembly attributes applicable to various types of codes.

Attribute	Design	Manufacture	Material	Account/ Schedule
Material	X	X	X	
Diameter	X	X	X	
Wall thickness	X	X	X	
Pipe length			X	
# cuts		X		
Bend radius		X		
# bends		X		
Type of joints		X		
# of joints		X		
Fitting ID, no.	X		X	
Component ID, no.	X		X	
Overall dimensions	X			
Configuration	X	X		
Surface treatment	X	X		
Inspection	X	X		
Drilling, threading		X		
Final assembly		X		
Total weight		X		
System (SWBS)				X
Ship				X
Unit				X
Pallet				X
Piece ID				X
Start date				X
Comp. date				X

A design code must describe the form, fit, and function of the assembly. Overall dimensions and configuration are necessary to describe form and fit. Fit would also depend on fitting identification for the description of end fittings, such as flanges. Function would depend on material, wall thickness, component identification (valves, strainers, etc.), surface treatment, and inspection requirements. A code to allow design recall of pipe assemblies would therefore be extremely ambitious, and it will not be attempted here. Design recall of very simple assemblies and subassemblies might be feasible and does warrant further attention, though none will be given to it in this thesis.

Developing a material code would similarly involve the arduous task of codifying fitting and component descriptions. Shipyard supply systems typically use eight digits to identify parts such as valves and fittings. Even if it were possible be reduce that somewhat, it would still take a prohibitive number of digits to identify the material requirements for an assembly with multiple fittings and components. It also is not clear that there is a real advantage to consolidating the material requirements list into a long single code, and this will therefore not be attempted. Although "competitive shipbuilders regard computer-aided material definition as their most important computer application,"(10) this does not require coding the material requirements list (MRL) in a GT fashion. It is a separate issue. One very useful output of a partial material code, however, could be the development of a cutting plan. If the length of a given type and size of pipe for each assembly were known, the software program could determine a cutting plan to minimize the scrap pipe left over after cutting the raw pipe stock. At least two shipyards already do this independently of their coding schemes. Use of the code as the data base for the cutting plan will be considered in the section on code development. Inclusion of manufacturing attributes and accounting information will also be considered. Before attempting to design a new code, though, it is worthwhile to examine two piping assembly codes currently in use.

6.2 Existing Pipe Assembly Codes

Todd Shipyards in San Pedro, California, and National Steel and Shipbuilding Company (NASSCO) in San Diego, California, both employ simple codes to aid the operation of their pipe shops. Both will be presented, explained, and analyzed.

6.2.1 Todd Shipyards(91)

Todd uses a 2-digit shop routing code to group pipe assemblies into one of 11 families, as shown in Table 6.4. This is not a GT code per se in that the digits do not have fixed meanings in either a monocode or polycode fashion. Nevertheless, it does form product families, which are shown in Figure 6-2. The first digit indicates the general complexity of the assembly, unless it is a four, in which case it indicates NDT requirements. The second digit indicates pipe diameter less than 3 1/2 inches if it is a blank, 3 1/2 inches or above if it is an "L," and brazing instead of welding if it is a "C." The code does a very good job at what it is intended to do--give the general route through the shop that the assembly will follow. This is a rough form of variant-based process planning, although it obviously could not produce a detailed process sequence. Similarly, it identifies the basic equipment that will be used in the fabrication process (large bender, small bender, welding booth, brazing table, etc.), although it does not provide enough information for formal process flow lane development. Although it identifies which bending machine would be used, it does not identify the required die size, so it could not be used to reduce bender setup time. By identifying NDT requirements, it could reduce bevel machine setup time, since Todd uses a different bevel angle for NDT quality welds. Finally, the code could be used for work content estimating and workload balancing, but only in a very, very general sense. The code obviously is not intended to be used for design recall, material planning, or accounting. Todd uses a separate code for accounting purposes.

Table 6.4. Todd Shipyards' pipe shop routing code.

CODE	DESCRIPTION
1	Straight pipe or pipe requiring bending only, 3-1/2" IPS and below.
2	Straight pipe with welded fittings, 3-1/2" IPS and below.
3	Complex assemblies which require subassembly, 3-1/2" and below.
4	Assemblies requiring NDT quality welding 3-1/2" and below.
1L	Straight pipe or pipe requiring bending only, 4" IPS and above.
2L	Straight pipe with welded fittings 4" IPS and above.
3L	Complex assemblies which require subassembly, 4" IPS and above.
4L	Assemblies requiring NDT quality welding 4" IPS and above.
2C	Straight pipe with brazed fittings.
3C	Complex brazed assemblies which require subassembly.
4C	Assemblies requiring NDT quality brazing.

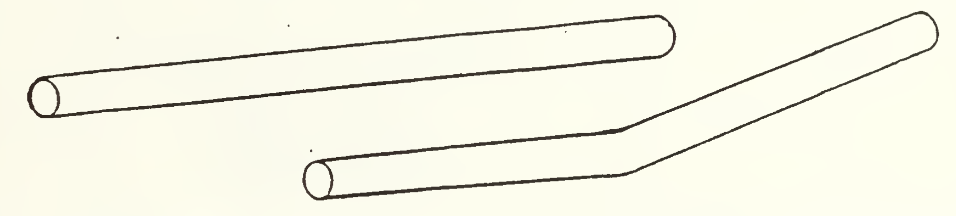
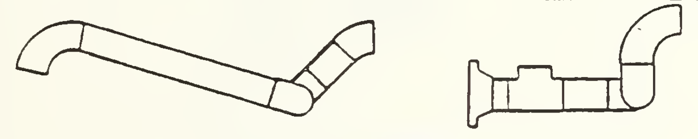
CODE	DESCRIPTION OF CONFIGURATION
1, 1L	
2, 2C, 2L	
3, 3C, 3L	
4, 4C, 4L	Any piping configuration requiring non-destructive testing. (X-ray, dye penetrant, ultrasonic, magnetic particle)

Figure 6-2. Todd shipyards' pipe assembly families.

6.2.2 NASSCO[92]

The NASSCO code is a more formal four-digit polycode which identifies the following attributes:

(1) Material

(2) Configuration

(3) Assembly

(4) Treatment

The attribute descriptions are listed in Table 6.5. A total of 288 families can be mathematically generated by the digits, but some of those would represent contradictory attributes. For example, a "no bending" configuration could not also be a "complex" assembly." There are 78 consistent families that NASSCO actually manufactures in its construction of

Table 6.5. NASSCO code attribute descriptions.

Material Attribute	
1	Ferrous
2	Non-ferrous
3	Other (flex hoses)
Configuration Attribute	
0	No Bending
1	Large Bending
2	Medium Bending
3	Small Bending
Assembly Attribute	
0	No Assembly
1	Large Straight
2	Small Straight
3	Large Complex
4	Small Complex
5	Special
Treatment Attribute	
0	No treatment
1	Clean/Paint
2	Clean/Galvanize/Paint
3	Clean/Galvanize

hospital ships. This code is similar to Todd's in that its primary purpose is to establish shop routes for the families. NASSCO divides its pipe shop into five work stations, as listed in Table 6.6. As can be

Table 6.6. NASSCO pipe shop work station.

Station	Process	Activities
114	Preparation	In-process storage, blasting, cutting
115	Bending	Bending
116	Assembly	Fitting, welding, brazing, bolting
117	Treatment	Cleaning, galvanizing, painting
118	Palletize	Kitting, storage

seen, these are fairly broad work stations, with four of the five performing multiple functions. NASSCO uses the code to form families and establish the routing sequence through the workstations for each family. In process planning capabilities, it is somewhat more detailed than Todd's code, which does not include treatment, does not define assembly complexity as thoroughly, and does not contain any information on the size of brazed pipe. Todd's however, does include inspection requirements, which is most likely a reflection of the difference in the types of ships that Todd and NASSCO build. NASSCO's code also duplicates some information, with both the second and third digits indicating pipe size.

In addition to establishing shop routing by family, NASSCO estimates time and labor manhours at each station for each family. It does this in a very general manner, though. For example, consider the way in which labor expenditure is calculated for a medium-bending family (second digit= 2) at work station 115 (bender). Actual process time for the medium bender using two workers is estimated to be 4.5 minutes per

bend, or 9 man-minutes per bend. A study done at NASSCO (referred to as the Waterman Contract) concluded that there are an average of 1.4 bends in a medium-sized assembly (1.4 × 9 = 12.6 man-minutes per assembly). However, the actual bend time represents only 40% of the time on station, with 60% being non-process time (12.6/0.4 = 32 man-minutes at station 115 for a medium-bending family member). NASSCO then assigns three days at work station 115 for calculating total through-put time. Two points are immediately obvious. First, a lot of float time is built into the through-put schedule. Second, the process times are based on statistical averages rather than each particular assembly. This limits the ability of the code to be used for workload balancing, since an assembly with one weld could be indistinguishable (in the code) from an assembly with eight welds. Furthermore, all assemblies requiring any manual assembly are classified as being complex, regardless of the number (or lack of) welds or brazes. Work content analysis is similarly limited, and setup time, although included in the time estimating algorithm, cannot be reduced with this code.

Nevertheless, the NASSCO code does a good job in establishing shop routes and in roughly estimating through-put time and labor time for each family. It provides more information than Todd's code, as it should since it has twice as many digits. Although the time and labor analysis is fairly general, it is probably adequate for NASSCO's current shop operations and workload. By using such a large amount of float time, NASSCO never presses their system to its limits. While this is safe, it precludes the achievement of optimum shop efficiency.

6.3 New Code Development

It was originally decided to develop a comprehensive code to include all manufacturing attributes as well as accounting information. This, unfortunately, resulted in a 24-digit numeric code that still did not fully describe configuration and had numerous other shortfalls. The

attributes identified by the code are listed in Table 6.7. Wall thickness could be given in ten intervals (0-9), as could pipe diameter and length. This code allows for two different pipe diameters in the same assembly, and it identifies the operations that will occur on each. Pipe length was included for cutting plan generation. Total number of fittings was included to give an idea of overall complexity and assembly time. Unfortunately, though, this code is a good example of not properly identifying the intended code use and using that as a basis for attribute description.

Table 6.7. First attempt at a comprehensive code.

Digit	Attribute
1	Material
2	Wall thickness
3	No. of fittings
4	First pipe: diameter
5	Length
6	No. of cuts
7	No. of bends
8	No. of joints
9	Second pipe: diameter
10	Length
11	No. of cuts
12	No. of bends
13	No. of joints
14	Special assembly requirements (drill, thread, crane)
15	NDT requirements
16	Treatment
17	System (SWBS)
18	System (SWBS)
19	System (SWBS)
20	Ship
21	Ship
22	Unit
23	Unit
24	Unit

First, material and wall thickness (and hence raw pipe material) cannot be uniquely identified with one numeric digit each. To create a cutting plan requires not just the basic material (steel, CuNi, etc.) but the specific alloy (to uniquely identify the pipe). Wall thickness would have to be known precisely rather than within one of ten intervals. However, switching to an alphanumeric code could uniquely identify standard pipe materials and schedule numbers, since it would allow 26 choices per digit. Length, though, should be identified to within 1/8 inch (which is the standard shop cutting tolerance). Using a possible length range of 20 ft necessitates 1920 length intervals. This would require three letters or four numeric digits. While it might be possible to solve any coding problem by throwing enough digits at it, it was decided here not to try to use the code to create the cutting plan. The MRL could be used as the cutting plan data base, as is the practice at Todd and NASSCO. It was also decided to use an alphanumeric code, since that would allow pipe diameter (for standard pipe sizes) to be uniquely identified by one digit.

The second major shortcoming is that although the number of joints in each pipe is specified, it is not specified whether those are welds or brazes. The material identification would answer that, unless it were CuNi, which can be either welded or brazed. Third, there's really no reason to include all of the accounting information in the code. This is a matter of shipyard preference. Accounting information, like the MRL, will have to be placed somewhere, and some yards might prefer to include it in one consolidated code; but those digits should be added to the code as a suffix or prefix on an "as-desired" basis.

In redesigning the code, it was desired to shorten it, to restrict the number of attributes to those really necessary for the intended end use, and to ensure that those attributes are adequately addressed. Although longer codes are in commercial use today, a shorter code is always preferable if it can accomplish its task. A shorter code both saves time that is spent on coding each assembly and would probably meet with less

resistance from managers who are unfamiliar with GT. The first task, therefore, was to clearly identify the end uses of the code. The primary uses of this code will be to reduce setup time and to balance the workload. Secondary uses will be process planning, process flow lane (work cell) development, and work content estimating.

Table 6.2 summarized setup time requirements for all pipe shop operations. Only die and clamp changing on the bending machines entailed a significant setup time, and it will be the only stepup time considered by the code. Mandrel setup time will not be addressed because virtually every pipe requires a different mandrel. To save significant mandrel setup time would require batching together pipes that might not otherwise be started for quite some time. Although a more rigorous analysis should be done to substantiate this, it is believed that the disadvantage of increased in-process inventory would outweigh any advantage from decreased setup time. Reduction of setup time will therefore require only two digits: pipe diameter and bend radius. This implicitly assumes two things: first, that all the pipe in the assembly is of the same diameter, and second, that all the bends are of the same radius. While the first code allowed for two pipe sizes, this code will only allow for one. Where more than one size is present in the assembly, that pipe representing the greatest amount of work will be the diameter shown in the code. To justify this restriction, 69 firemain and flushing system detailed sketches (for FFG-7) were examined for multiple pipe sizes. Ninety percent had only one pipe size. Seven percent had two, and 3 percent had three or more. This is admittedly a rather small sample size and is taken from only one system, but it is believed to be representative of the ship as a whole. The pipe size distribution in the firemain and flushing system is no more concentrated at one or two sizes than in any other system. Consequently, assemblies with multiple pipe sizes are no more likely to occur in other systems. For single pipe size assemblies, shop experience and a study of these same drawings indicate that a single bend radius is almost always used.

The other primary code function will be for use in workload balancing. The goal of workload balancing is to evenly distribute work throughout the shop and to prevent bottlenecks. It might not be necessary, however, to fully quantify every work process that will be done to each assembly. Rather, only the critical processes need to be specified. Threading machines, for example, will sit idle most of the time no matter how much batching and balancing is done. Shop threading capacity cannot be reduced without eliminating it altogether, and it is highly unlikely that there would ever be a bottleneck at the threading machine, so inclusion of threading requirements in the code would not serve a useful function in workload balancing. Cutting and drilling, although more common, will not be included for the same basic reason--they simply are not limiting shop functions. Cutting is quick and simple and done to all pipes. Drilling, though not quite as simple, is still fairly quick and is not commonly done. It is difficult to imagine a backlog at the drilling station. Furthermore, the equipment does not represent a major capital investment, and the labor requirements are minimal.

The only processes in which bottlenecks normally occur are welding and brazing, including fit up. The number of welds and the number of brazes will therefore be identified by the code. Although butt welds are more difficult and take more time than socket welds, the code will not explicitly distinguish between the two. The total time difference (between a butt and a socket) for manual fit up and welding of a 3-inch joint in stainless steel pipe is 15 minutes (75 vs 60). While this is not a negligible difference, it is small enough that the workload balancing algorithms should be able to minimize its adverse impact. Joints larger than three inches are almost always butt welded, so the diameter digit would give some indication of the type of weld joint. Pipe diameter would also be necessary input into the balancing algorithms since it has a major effect on fit up and weld time. Furthermore, the pipe material is critical in determining both the welding process and the welding time, so material will be identified in the code.

Bending, final assembly, and quality assurance inspection requirements will also be included in the code for balancing purposes. Bending does not normally produce a bottleneck, but the number of bends would nevertheless be valuable information for two reasons. First, batching to reduce bending setup time could produce delays at the bending machines, so the number of bends would be vital information in avoiding such a backlog. Second, bending machines represent a substantial capital investment, so decisions to remedy chronic balancing problems through bending facilities expansion or reduction would be major decisions and would require thorough bending information. This could also be considered a work content function; regardless, the number of bends will be included as a digit.

Final assembly is simply the making up of mechanical joints after all welding and brazing are complete. It requires no expensive equipment, but it is labor intensive and should therefore be included to help balance shop manning. The number of mechanical joints will be used as a general indication of final assembly difficulty and duration. Time estimates will also be dependent on pipe diameter, since larger joints take longer to assemble.

Quality assurance (NDT) inspection requirements will be included for two reasons. First, they impact on labor requirements. Only certain welders are qualified to do NDT quality welding. To prevent those welders from becoming overloaded, NDT quality welds should be identified.

Second, the persons performing NDT inspections are not pipefitters. They work for the QA department and only come to the pipe shop when called to do so (a form of setup time). Identifying QA requirements in the code would allow the shop schedulers (via the balancing software) to group assemblies together in a manner that optimizes the use of quality assurance personnel.

To summarize so far, reduction of setup time and workload balancing would require the following attributes to be identified by the code: pipe diameter, bend radius, number of welds, number of brazes, material,

number of bends, number of mechanical joints, and inspection requirements.

The secondary uses of the code will be for rough process planning (shop routing), process flow lane development, and work content estimating. Some aspects of work content estimating are essential to workload balancing and have already been discussed. Of secondary importance for this code are the aspects of work content estimating that are useful in and of themselves (as the basis for statistical surveys, for example).

The only additional attribute that must be described for these functions is treatment (clean, paint, and galvanize). Treatment was not included as a balancing attribute because of the nature of the work. Cleaning is done in a large tank that can accommodate many pipe pieces at one time, and the pieces are left in the tank only briefly. Painting is done outside the shop in the shipyard painting facilities, which are typically so vast that even extreme fluctuations in the pipe assembly workload would have no overall impact. Galvanization is generally subcontracted to a vendor, and it is extremely rare. It is therefore difficult to conceive of these processes creating bottlenecks. Painting and galvanization, however, do take time since they are done at remote locations, so they must be considered in shop routing and through-put time calculations. Cleaning is also of interest to shop routing, although it doesn't have a large effect on through-put time. Cutting is again neglected, because every pipe goes through cutting. Whether one cut or many cuts are made makes very little difference time-wise. Drilling and threading could be included for shop routing, but is not believed that there would be a real advantage to this. If the code were intended to be used to produce detailed process plans, then it would certainly be necessary; however, the detail sketch will accompany the assembly anyway, and drilling or threading requirements would show up on that.

6.4 Finalized Code

In order to adequately perform its intended functions, the code must describe the attributes listed in Table 6.8. By using an alpha numeric code, each attribute can be adequately described by one digit. The attribute descriptions are listed in Table 6.9. Pipe diameter is described by a letter that identifies any of the standard pipe sizes plus several others that are commonly used on ships (5/8, 7/8, and 1-1/8). There are several nonstandard pipe sizes that are occasionally used on ships that are not explicitly identified by the attribute description. These would be coded as the next higher diameter, since that is the die size that would be used for bending such a pipe. (This also raises the design question: why not standard size pipes, even if that means a minor weight penalty in some cases? Standardization and inventory control would benefit.) The bend radius digit simply gives the bend radius in pipe diameters. For assemblies without any bends, a zero would be used.

Table 6.8. Finalized code attributes.

Digit	Attribute
1	Pipe diameter
2	Bend radius
3	Material
4	Number of bends
5	Number of welds
6	Number of brazes
7	Final assembly
8	Treatment
9	Inspection

Material is not uniquely identified by the material digit--there are, for example, several types of stainless steel in common use in piping systems. However, the general manufacturing procedures are the same for all of them, so there is no need to distinguish them in the code.

Table 6.9. Code attribute descriptions.

Pipe diameter:	A	1/8	M	2-1/2
	B	1/4	N	3
	C	3/8	O	3-1/2
	D	1/2	P	4
	E	5/8	Q	5
	F	3/4	R	6
	G	7/8	S	8
	H	1	T	10
	I	1-1/8	U	12
	J	1-1/4	V	14
	K	1-1/2	W	16
	L	2		
Bend radius:	0	No bend		
	2	2D		
	3	3D		
	5	5D		
Material:	1	Steel		
	2	Stainless steel		
	3	Aluminum		
	4	Copper-nickel		
	5	Copper		
	6	Brass		
	7	Other (flex hoses, etc.)		
No. of bends:	0-9			
No. of welds:	0-9	(no. of welded joints)		
No. of brazes:	0-9	(no. of brazed joints)		
Final assembly	0-9	(no. of mechanical joints)		
Treatment:	0	None		
	1	Clean		
	2	Clean/paint		
	3	Clean/galvanize		
	4	Clean/galvanize/paint		
Inspection:	A	None		
	B	Visual		
	C	UT		
	D	PT		
	E	MT		
	F	RT		
	G	PT and RT		
	H	MT and RT		
	I-O	Same as B-H plus hydro		

If a detailed process instruction were to be generated on the sole basis of the code, such a distinction would have to be made. Material identification number seven (other) is used for flex hoses and any other type of piping that does not use the normal pipe shop processes. Alternatively, the shop could simply decide not to code such assemblies of all.

The fourth, fifth, sixth, and seventh digits give a numerical count of the number of bends, welds, brazes, and mechanical joints, respectively. Nine would have to indicate nine or more. It is believed that very few assemblies have more than nine of any of these. If future experience proved otherwise, changing any of these digits to a letter designation would alleviate the shortfall. Although computers can deal as easily with letters as with numbers, numeric designators have been used for these attributes to make the code more meaningful to humans. The treatment and inspection digits cover all possible combinations of treatment and inspection processes. Inspection combinations that are never used in practice (such as UT and MT) are not included.

6.5 Code Limitations

The code has some definite limitations, both informationally and functionally, some of which have already been discussed. To summarize them, the code will accurately describe only an assembly with one pipe diameter and one material. It does not identify certain processes, such as cutting, drilling, and threading. It does not distinguish between socket and butt welds. Perhaps most importantly, it does not give detailed sequence information. For example, two assemblies, each with four brazed joints, would both have a "4" as the sixth digit and possibly identical codes altogether, even though the sequential interaction between fit up and brazing could be vastly different for the two assemblies. Similarly, the inspection description does not distinguish between inspection of the completed product and in-process inspection (such as PT of a root pass). These informational limitations primarily limit the code's utility for process planning. General shop routes are all that this code will produce--somewhat more detailed than the Todd or NASSCO code, but not significantly. The code's strong point is reduction

of setup time, since it uniquely identifies the setup requirements for bending, the only shop process that involves significant setup time. Previous codes did not do this.

The code can be used for workload balancing with for greater accuracy than was possible with previous codes, but it still contians some workload generalizations. This rases the question: how accurately should a code identify the workload requirements? Anyone who has personally observed a shipyard pipe shop in operation would probably answer that considerble slack could be allowed. The author would agree, but only for the manner in which pipe shops currently operate. All of the pipe shops that the author visited were in periods of low workload, so workload perturbations at any or all workstations were easily absorbed. During periods of heavy workload, however, balancing will become a much more important issue and greater workload forecasting accuracy will be required. If a shop never experiences a workload that strains its capacity, then it has too much capacity and is wasting money on excess labor and facilities. Furthermore, as pipe shops automate, tighter controls will be necessary to fully exploit the benefits of that automation. This code can help to identify targets for automation by its work content estimating capability. Unfortunately, it does not distinguish welds that can or cannot be automated, nor welds that should be completed prior to bending. Such distinctions would depend on configuration attributes that would be very difficult to code.

The practical use of this code will be examined further in the next chapter. The attempt here was to design a code that could be used for several important functions,not all of which can be individually optimized simultaneously. Reducing setup time, for example, might be complete against workload balancing. Given enough information, it should be possible to produce an overall optimization scheme through the development of process flow lanes. Even without going that far, the code could still be used to boost productivity by attacking individual problem areas.

CHAPTER 7

GT PIPE CODE APPLICATIONS

The code developed in Chapter 6 will now be applied to various pipe assemblies. Shop routing of these assemblies will be discussed, and workload balancing and setup time reduction will be analyzed using quantitative data from FFG-7 piping systems.

7.1 Assembly Coding

Appendix A shows the detailed sketches of four pipe assemblies. The first three are CuNi assemblies from the FFG-7 firemain and flushing system. The fourth is a hypothetical four-inch ips steel assembly which requires final MT. The CuNi assemblies are all brazed and do not require quality assurance inspection. The coding process is simple, and the codes are listed in Table 7.1.

Table 7.1. GT codes for assemblies shown in Appendix A.

Assembly	Code
1	N0400100A
2	M3430220A
3	N0400820A
4	P3117001E

Assembly #1 is a 3" nominal pipe size (first digit = N) CuNi assembly (third digit = 4) with no bends or welds, one braze, and no mechanical joints. Digits two and four through seven are therefore 0, 0, 0, 1, and 0, respectively. There are no treatment or inspection requirements, so the final two digits are 0A. Assembly #2 is 2-1/2" nominal pipe size (first digit = M) with 7-1/2" radius bends (3D bends, second digit = 3). It is also CuNi (third digit = 4). There are three bends, no welds, two brazes, and two mechanical joints (one on each side of valve V-47), so the fourth through seventh digits are 3, 0, 2, and 2, respectively. It also has no treatment or inspection requirements, making 0A the last two digits. Assembly #3 is similar to #2, except that it is 3" nominal pipe size and has 8 brazes and no bends. Assembly #4 is a 4" ips (first digit = P) steel assembly (third digit = 1) with a single 3D bend (second digit = 3, fourth digit = 1). There are 7 welds, no brazes, and no mechanical joints, making 700 the next three digits. Final cleaning and MT are required, so 1 and E are the eighth and ninth digits, respectively.

7.2 Shop Routing

The layout of the major workstations in a typical shipyard pipe shop is shown in Figure 7.1. It accurately represents the functional layout and, to some degree, the relative sizes and shapes of the workstations; however, it is not to scale and does not accurately represent floor space allocation. Painting and galvanizing, which are not normally done in the shop, are not included. Drilling and threading are similarly omitted. End-preparation will be considered to be done at either the cutting of fit-up workstations; hence, a separate beveling/end-preparation workstation is not included.

The general route through the shop can be determined from the code; however, some of the details of the shop routing will depend on assembly features that are not included in the code. For assembly #1,

the code identifies that other than cutting, the assembly will require only fit up and brazing of one joint. In this case the code contains sufficient information to specify the exact shop route, which is shown in Figure 7.2. In all the shop routing figures, each line represents a distinct piece of pipe. Flow between workstations is represented by solid lines. Flow through workstations is represented by dashed lines. Multiple lines converging into a single line indicates joining, either by fit up for welding/brazing or by final assembly.

In order to determine the shop routes for the remaining three assemblies, several assumptions regarding shop practice must be made. First, assume that all brazing and welding is done after bending. Although not always desirable, this is in fact the normal practice in most pipe shops. Second, assume that all straight assemblies or subassemblies are welded with the semi-automatic welding equipment. Delaying bending until after welding would allow semi-automatic welding in some cases in which it would otherwise not be possible. Identifying those cases, though, is beyond the capability of this code. For the analysis here, therefore, normal shop practice will be used. Third, assume that bending is always followed by cleaning to remove the mandrel oil. Finally, assume that all mechanical joints are made up after welding and brazing are completed. These last two assumptions are generally the case, although there could be exceptions.

Assembly #2's code identifies that it must be bent, brazed, and final assembled. Since it is CuNi, it is automatically known that it must be annealed prior to bending. Cleaning will automatically follow bending. The general route is therefore known to proceed in the following order: cut, anneal, bend, clean, fit up, braze, and final assemble. For the particular assembly (with only two brazes), that is sufficient to uniquely identify the route, which is shown in Figure 7.3.

Assembly #3 is somewhat more complicated, with four separate pipe pieces, eight brazes, and two mechanical joints. To clarify the routing explanation, the pipe pieces have been designated p1, p2, p3, and p4 in the diagram in Appendix A. This assembly points out the limitations a pipe code faces when being used for generative process planning with current shop practices. For this assembly, the code only indicates that it must be brazed and final assembled. The exact sequence would be determined by the lead pipefitter to whom the assembly is assigned, but it probably would be as shown in Figure 7.4. After cutting, p1 would be fitted with its elbow and flange, then brazed and acid dipped. It then would be ready for final assembly. p2 and p3 would be fitted with the elbow between them and the flange on the end of p2. Brazing of the three joints would be next, followed by acid dip and return to the fit up table. The other elbow, p4, and the tee would be added to this subassembly, and those joints would then be brazed and dipped. Next, it would be joined with the valve (V1) and the other subassembly (containing p1) in final assembly.

Final assembly and fit up frequently take place at the same location. The lead pipefitter for that assembly follows it through all stages of fabrication. He cuts the pipe, fits up the joints, takes it to the brazing station, brings it back, and final assembles it. Only brazing, welding, and, in some shops, bending are done by specialized workers. The unique nature of each pipe assembly encourages this type of work organization. One advancement that would help to standardize process routes would be the use of induction brazing. Induction brazing can be done without the physical motion required of the workpiece and brazer in flame brazing, since the coils uniformly heat the entire joint area. This would enable all joints to be fit up prior to brazing in all but the most complex assemblies. Induction brazing is not currently approved for use on most naval piping systems; further investigation into its use would therefore appear to be warranted.

Assembly #4 is identified by the code as requiring one bend, seven welds, final cleaning, and MT inspection. The shop route for this assembly is shown in Figure 7.5. As with assembly #3, planning the exact route requires configuration information that is not contained within the code. Because six of the seven welds lie on a linear subassembly, those six can all be made with the semi-automatic welding equipment. Only the weld joining the bent pipe piece to the tee must be done by hand. The shop route would therefore join the four straight pipe pieces, the valves, and the tee at the fit-up station, then weld all these at the automatic welding station. The other pipe piece would be bent, cleaned, then fit up and welded to the completed linear subassembly. Figure 7.5 shows the fully welded assembly going to the NDT station for MT. In reality, though, MT equipment is very portable, and inspection could be done at the welding station. Whether each weld is inspected after it is finished is purely a matter of discretion. If weld repairs would be made much more difficult by further fabrication of the assembly, inspection should be done before proceeding to the next joints. Generally, though, all joints would be inspected at the end (unless in-process inspection was required).

Final cleaning will similarly depend on information not contained in the code. Since assembly #4 has valves in it, the completed assembly would not be dipped in the cleaning tank. Rather, each pipe piece would be cleaned prior to joining, and, if necessary, the completed assembly would be flushed. If the raw pipe had a significant amount of scale in it, shot blasting might be required prior to fabrication. For the sake of clarity, cleaning details are not included in Figure 7.5.

The GT code gives a general idea of what the shop routing for a given assembly will be. For many simple assemblies, the routing is exact. For complex assemblies, additional information is required, and this information generally concerns configuration and would be very difficult to code. Since this code is not intended to be used for exact

generative process planning, this limitation is not significant. Regardless of all the process sequencing details, the code does contain total work content information and therefore could serve as a basis for through-put time estimating. Since the code breaks down the work content by workstation, it is also very useful for workload balancing, although detailed routing information would be necessary for highly accurate balancing.

7.3 Workload Balancing

The previous section analyzed shop routing through a functional diagram that bore some similarity to the actual physical shop layout. This section will examine routing through a shop routing "tree," as shown in Figure 7.6. Each block in the tree represents a distinct process, such as cutting, bending, brazing, etc. Each assembly follows a path through the tree that includes all the processes which must be done to that assembly. The intent is simply to identify those processes which a given assembly will require. Each assembly is therefore considered in its entirety. Individual pipe pieces that do not require work are not shown separately. The only instance in which multiple branching is possible is for welding, since both hand welding and automatic welding can take place on the same assembly. The paths for assemblies one through four are shown in Figure 7.7 through 7.10, respectively.

The tree is basically divided into the two fabrication categories of welding and brazing. The left-hand side is for welded materials (steel, stainless steel, and aluminum). The right-hand side is for brazed materials (copper, copper-nickel, and brass). In the ensuing analysis, copper-nickel will be assumed to be brazed. When both categories use the same process, such as cutting (which is done independently of material), both path lines go through the same block. The blocks identify only the process, not the specific equipment. The large, medium, and small rotary benders are therefore grouped together into the same block. For actual shop workload balancing, equipment would have to be distinguished within each block.

Aluminum is a special case in that it is welded as ferrous materials are, but it is annealed prior to bending as copper and copper alloys are. It therefore has its own branch path through annealing, bending, and cleaning before rejoining steel and stainless steel for fit up and welding.

The paths are intended to show the sequence of the processes. The tree structure therefore assumes, as before, that all bending is done prior to welding or brazing, that cleaning always follows immediately after bending, and that mechanical joints are made up at the very end. The tree structure does not allow for assemblies with both brazing and welding (as could be the case for CuNi). Additionally, it does not specify the type of surface treatment or NDT inspection. These two blocks can be thought of as containing trees within them which consist of the various individual treatment and inspection processes, such as cleaning and radiography.

The shop routing tree can be a useful tool in visualizing work content estimating and workload balancing using the GT code. The code uniquely identifies the path through the tree for each assembly, with the only exception being that the code does not distinguish automatic welding from hand welding. In addition to identifying the processes, though, the code quantifies the workload for that process for each assembly (by specifying the number of bends, welds, brazes, etc.). That information could be shown by the width of the path lines going into each process block. The width scale for each block could be the number of times that process must be done to that assembly. Alternatively, the time for each process could be calculated and the path line width could represent time. This would incorporate information regarding different process times for different materials and pipe sizes and would put the entire diagram into one scale; it would therefore be a much more useful representation.

In order to demonstrate the GT code's utility for workload balancing, the routing tree will be used to analyze total work content on FFG-7 piping systems. The data on the piping systems is taken from a study

performed by IHI consultants for Bath Iron Works.[93] The study excluded gauge piping that is fabricated on board. It therefore came up with a total pipe length of 61,564 ft, compared to the 86,619 ft cited in Chapter 5. The difference of 25,000 ft seems excessive for gauge piping length. The methodology for determining the pipe length in the earlier (Todd) study is not known by the author, so this could account for part of the difference. The BIW study lengths were taken from the pipe material lists on the detailed pipe drawings. Some basic study conclusions are listed in Table 7.2. Table 7.3 lists the number of straight, bent, and total assembly by material.

Table 7.2. FFG piping system data.

Total number of assemblies	=	10,320
Number of straight assy	=	1,401
Number of bend assy	=	8,919
Total number of bends	=	14,357
Total number of cuts	=	21,505
Total number of fittings	=	27,435

Table 7.3. FFG piping assemblies by material.

Material	Straight	Bent	Total
Steel	263	1222	1485
Stainless Steel	95	574	669
Aluminum	30	174	204
Copper	563	4133	4696
Copper-Nickel	442	2812	3254
Brass	8	4	12
	1401	8919	10,320

The study did categorize the assemblies by their general level of complexity, based on the total number of fittings in the assembly. However, it did not distinguish mechanical from welded or brazed joints, and it grouped together assemblies with zero and one fitting. For the purpose of analysis, therefore, it will be assumed that half the simplest category of assemblies (zero or one fitting) have no fittings and require no welding or brazing. The other half, as well as all the more complex assemblies, require welding or brazing. While the total number of fittings was given as 27,435, and while the study broke this down into general functional categories of fittings, it did not categorize them by joining process (mechanical, welding, or brazing). It will be assumed that the fitting distribution is independent of material, and that 15% of the fittings are mechanically joined, the other 85% being welded or brazed. These assumptions result in the assembly data listed in Table 7.4.

Table 7.4. Estimated process and fitting distributions.

S, SS, Al:	
assemblies:	2358
welded:	1730
non-welded:	628
welded fittings:	5328
mechanical fittings:	941
Cu, CuNi, Br:	
assemblies:	7962
brazed:	6949
non-brazed:	1013
brazed fittings:	17,991
mechanical fittings:	3175

Of the 1730 welded assemblies, it will be assumed that the same straight/bent ratio holds as is true for the assemblies overall (13.6% straight, 86.4% bent). That results in 235 straight welded assemblies, and 1495 bent welded assemblies. If we further assume that the welded

fittings are evenly distributed between the straight and bent assemblies, then there are 724 welded fittings on straight assemblies, and 4604 welded fittings on bent assemblies. This is probably a weak assumption, since straight assemblies are very simple and would tend to have fewer fittings. Finally, if we assume that all the fittings on the straight assemblies can be welded with the semi-automatic welding equipment and estimate that one-fourth of the fittings on bent assemblies can be semi-automatically welded, then 3,453 fittings must be hand welded, and 1,875 fittings can be semi-automatically welded. Some fittings will be welded or brazed on both sides. Others will only be welded or brazed on one side, with the other side being made up during installation on board. We will assume a 50% split here, so that there are 1.5 welds or brazes per fitting. Also assume that for every three welded fittings, there is one butt weld joining two pipe pieces directly, and that the butt weld distribution between hand and automatic is the same as for fittings. Mechanical components tend to be installed on both sides in the shop, so estimate 1.9 mechanical joints per mechanical fitting. These assumptions result in the joint distribution listed in Table 7.5.

Table 7.5. Estimated joint distribution.

S, SS, Al:	
Hand welded joints:	6331
Auto welded joints:	3438
Mechanical joints:	1788
Cu, CuNi, Br:	
Brazed joints:	26,987
Mechanical joints:	6033

In addition to the bending data included in Table 7.3, the study counted the actual number of bends for each material. This data is listed in Table 7.6.

Table 7.6. FFG pipe bends.

Steel	1714
Stainless Steel	764
Aluminum	195
Copper	7401
Copper-Nickel	4276
Brass	7
	14,357

No data was provided by the study regarding NDT inspection requirement and surface treatment. For all of the other processes, though, the real and estimated data can be used to sketch a "loaded" shop routing tree. Figure 7.11 shows a routing tree loaded with the entire FFG piping workload. All numbers in Figure 7.11 are numbers of assemblies, except for the numbers on the branches through the hand and automatic welding blocks. These numbers are followed by an (f) and denote the number of fittings. One additional assumption that went into Figure 7.11 regards the number of final assembled assemblies. It is taken as the number of welded/brazed assemblies multiplied by twice the ratio of mechanical fittings to welded/brazed fittings. The logic behind this is that if 5328 welded fittings result in 1730 welded assemblies, then there are an average of 3.1 welded fittings per welded assembly. It is not reasonable to assume a mechanical fitting density that high, so it is assumed to be half as much. The number of mechanically assembled assemblies is therefore:

$$N_{ma} = N_{wba} \times 2 \frac{N_{mf}}{N_{wbf}}$$

$$= \frac{2}{N_{wbf}/N_{wba}} \times N_{mf}$$

$$= (2/\rho_{wbf}) \times N_{mf} = 611 \text{ (in S, SS, Al assemblies)}$$

where

N_{ma} = Number of mechanical assemblies

N_{wba} = Number of welded/brazed assemblies

N_{mf} = Number of mechanical fittings

N_{wbf} = Number of welded/brazed fittings

ρ_{wbf} = Density of welded/brazed fittings

Similarly, 2453 copper and copper alloy assemblies require final assembly.

While loading the routing tree with numbers of assemblies might be interesting, it is too general to be of practical use. Figure 7-12 shows the routing tree loaded with the number of process applications--number of cuts, bends, welds, brazes, mechanical joints, etc. The number of cuts is derived from applying the ratio of number of assemblies to the total number of cuts. 22.8% of the assemblies are steel, stainless steel, or aluminum, so it is assumed that 22.8% of the total cuts are in steel, stainless steel, or aluminum pipe. In actuality, that distinction matters very little, and cutting information is not even included in the GT code to begin with. Relative loading in Figure 7.12 is shown with only numbers, not path width. Figure 7.12 is more usable than Figure 7.11 since it quantifies the process data rather than quantifying aggregate assembly data.

The GT code could serve as the data base from which to produce loaded routing trees for any given group of assemblies. The only information presented in Figure 7.12 that could not come from the GT code is number of cuts and the division between hand and automatic welding. Cutting information was intentionally neglected for reasons outlined in Chapter 6. Hand versus automatic welding is simply too difficult to code.

To be truly useful for workload balancing, two additional steps would need to be taken. First, a time or labor calculating algorithm would need to be included in the code processing software. Second, scheduling data would need to accompany the code. That would enable the shop to look at the actual workstation workload for any given time period, and take preventive action to avoid impending bottlenecks or, conversely, underutilization of manpower or equipment. Actual scheduling data will not be included in this thesis. A simple labor algorithm, however, will be applied to the process data in order to produce a time or labor loaded routing tree.

The basis of the labor algorithm will be the NASSCO report referenced in Chapter 6.[92] It presented recommended labor planning for a number of pipe fabrication processes. These requirements include non-process time and are listed in man-minutes in Table 7.7. Although

Table 7.7. Workstation labor requirements for pipe shop processes. (Non-process time included.)

Cutting	All sizes	5.6 man-minutes/cut
Bending	≤2.5" 2.5" - 4" >4"	15 man-minutes/bend 22.5 52.5
Weld fit up	≤4" >4"	13.1 man-minutes/fitting 26.1
Hand welding	≤4" >4"	11.6 + 5 (checkout) 24.8 + 5
Autowelding	≤4" >4"	8.1 + 5 17.3 + 5
Braze fit up	≤4" >4"	13.1 26.1
Brazing	≤4" >4"	7.7 + 5 16.5 + 5
Final assy	≤4" >4"	8.7 + 5 18.6 + 5

non-process time was not specifically defined, it is believed to be just setup time. It was uniformly assumed to be 60% of the total time listed for each process. The report did not distinguish welding time from brazing time. Therefore, brazing fit-up time was estimated to be equal to welding fit-up time, and actual brazing time was estimated to be two thirds of the hand welding time. Mechanical assembly time was similarly not included in the NASSCO report, so it has been estimated to be three fourths of the hand welding time. Five minutes checkout time is allocated to each assembled fitting.

The labor requirements listed in Table 7.7 are per fitting, not per joint. In calculating the total labor requirements for all the FFG-7 piping assemblies, these numbers will be converted to a per-joint basis by dividing by the assumed number of joints per fitting (1.5 for welds and brazes, 1.9 for mechanical). Since Table 7.7 lists labor requirements rather than workstation time, workstation manning levels would have to be included in the workload balancing software. It is undoubtedly true that other shipyards might have significantly different time estimates for each process; nevertheless, these estimates are sufficient to produce a trial loaded tree for FFG piping assemblies.

Statistical data regarding size is required to proceed. The FFG piping study at BIW counted bends as a function of pipe size. The results are grouped together in Table 7.8 into the three discrete levels

Table 7.8. FFG bends as a function of pipe size.

Pipe Size	# Bends
≤ 2.5	12,293
2.5 - 4	1708
≥ 4	356

for which NASSCO gave separate time estimates. For all other processes, since size data was not included in the BIW study, it will be assumed that the size distribution is the same as the size distribution for pipe length given by the Todd study in Table 5.3, except that piping 1/2 inch and smaller will be neglected in order to make the Todd and BIW data compatible. Neglecting the very small pipes would seem to be justified by the fact that they are generally not fabricated in the shop anyway. All gauge piping and some other small diameter low pressure piping (such as for control air) is fabricated on board ship using hand tools. The bending size distribution should not be used for joints, because fittings are much more commonly used than bends on large pipes. Based on pipe length, the percentage breakdown by size for joints is shown in Table 7.9. This is, in fact, significantly different from the bending distribution, which has only 11.9% between 2.5 and 4 inches, and only 2.5% above 4 inches. Assume annealing has the same distribution as all of bending, and allow 2, 3, and 4 man-minutes to anneal the three respective pipe sizes.

Table 7.9. Estimated FFG joint sizes.

<table>
<tr><th>Size</th><th colspan="2">Percentage</th></tr>
<tr><td>≤2.5</td><td>77.8</td><td rowspan="2">} 94.2</td></tr>
<tr><td>2.5 - 4</td><td>16.4</td></tr>
<tr><td>≥4</td><td>5.8</td><td></td></tr>
</table>

It is now possible to calculate total labor time for each major workstation for all FFG-7 piping assemblies. The process repetitions shown in Figure 7-12 and distributed in size according to Tables 7.8 and 7.9 can simply be multiplied by the labor time estimates. Materials will be grouped together for this analysis when the process is not material dependent.

$$\text{Cutting:} \quad 21{,}505 \times 5.6 = 120{,}428 \text{ man-minutes}$$
$$= 2{,}007 \text{ man-hours}$$

$$\text{Annealing:} \quad (10{,}168 \times 2)(1414 \times 3) + (297 \times 4)$$
$$= 25{,}766 \text{ man-minutes}$$
$$= 429 \text{ man-hours}$$

$$\text{Bending:} \quad (12{,}293 \times 15) + (1708 \times 22.5) + (356 \times 52.5)$$
$$= 241{,}515 \text{ man-minutes}$$
$$= 4{,}025 \text{ man-hours}$$

Cleaning after bending is very quick, but does require transport time to and from the tanks. However, multiple bends on the same pipe would be cleaned simultaneously. There are 14,357 bends spread throughout 8,919 bent assemblies, for an average of 1.6 bends per assembly. Assume that all assembly bends are cleaned. Therefore, allow 3.7 man-minutes per bend for cleaning, or, equivalently, 6 minutes per bent assembly.

$$\text{Cleaning:} \quad 14{,}357 \times 3.7 = 53{,}121 \text{ man-minutes}$$
$$= 885 \text{ man-hours}$$

$$\text{Welding fit up:} \quad \frac{9769}{1.5}(0.942 \times 13.1 + 0.058 \times 26.1)$$
$$= 90{,}226 \text{ man-minutes}$$
$$= 1504 \text{ man-hours}$$

$$\text{Hand welding:} \quad \frac{6331}{1.5}(0.942 \times 16.6 + 0.058 \times 29.8)$$
$$= 73{,}295 \text{ man-minutes}$$
$$= 1222 \text{ man-hours}$$

$$\text{Auto welding:} \quad \frac{3488}{1.5}(0.942 \times 13.1 + 0.058 \times 22.3)$$
$$= 31{,}248 \text{ man-minutes}$$
$$= 521 \text{ man-hours}$$

Brazing fit up: $\frac{26,987}{1.5}$ (0.942 × 13.1 + 0.058 × 26.2)

= 251,051 man-minutes

= 4184 man-hours

Brazing: $\frac{26,987}{1.5}$ (0.942 × 12.7 + 0.058 × 21.5)

= 237,673 man-minutes

= 3961 man-hours

Final assembly: 7821 (0.942 × 8.9 + 0.058 × 13.3)

= 71,603 man-minutes

= 1193 man-hours

The labor estimates are summarized in Table 7-10. Figure 7.13 shows the resulting labor loaded routing tree. Estimates for NDT inspection and surface treatment will not be made due to lack of data. The total manhours of the processes analyzed in this chapter is approximately 20,000. This in but a fraction of the several hundred thousand man-hours typically spent by a shipyard pipe shop on an FFG-7. There are several reasons for this rather large difference.

First, the calculations considered only shop fabrication. For any given piping system, a rough rule of thumb is that 40% of the man-hours are spent on fabrication and 60% are spent on installation. Furthermore, some smaller systems are fabricated on board, requiring no shop work. If the difference in total pipe length between the Todd and BIW studies is due to Todd's inclusion of shipboard fabricated piping, then it amounts to a very significant 25,000 ft of piping (roughly a third of the total pipe length). Of the total pipe shop expenditures, therefore, perhaps only a hundred thousand man-hours are spent in the shop, and some of these are due to rework.

Second, the calculations did not include a number of pipe shop operations. Besides NDT, cleaning, drilling, and threading, a pipe shop also charges man-hours for work on flex hoses, waveguides, and, in some

Table 7.10. Estimated labor man hours for FFG piping fabrication.

Process	Man Hours
Cutting	2007
Annealing	429
Bending	4025
Cleaning	885
Weld fit up	1504
Hand welding	1222
Auto welding	521
Braze fit up	4184
Brazing	3961
Final assembly	979
	19,717

yards, refrigeration and air conditioning compressors. While it is doubtful that this work comprises a major share of a pipe shop's workload, it is not negligible.

Third, the calculations contained a number of gross estimates and assumptions. Therefore, while the results are believed to be qualitatively accurate, there could be large quantitative discrepancies. Along these same lines, the NASSCO labor estimates are based on NASSCO's experience building hospital ships. There is a high degree of uncertainty in applying these estimates to naval combatant ship construction. Although the basic processes involved are the same, the pipe materials and quality assurance standards could be sufficiently different to make the results questionable.

Finally, it is expected that there would be a fairly large difference between theoretical and actual shop expenditures. If there weren't any difference, then there would be little room for productivity improvement other than by reducing workstation time. While reducing workstation time is certainly an excellent target for productivity improvements, the

author believes that reduction of non-productive time between work-stations is another viable target. The ultimate goal of process flow lanes addresses both these issues.

For these types of calculations to be of practical use, the estimates on which they were based would have to be greatly refined. The GT code is a valuable tool for collecting the process data and organizing it into a usable data base. The time estimating algorithms require additional study to improve their accuracy. The code is compatible with very exact labor requirements data. Whether such data can actually be collected remains to be seen. The loosely organized work flow in existing pipe shops makes the collection of accurate time and labor data difficult. Finally, scheduling information would need to be incorporated in order to have a viable workload balancing tool. With this additional data and information, the GT pipe code could be of great value in increasing pipe shop productivity.

7.4 Setup Time

Bending setup time can be minimized by using the code to identify assemblies with identical bending machine die and clamp lock requirements. However, this effort must be balanced against the increase in process inventory that would result. At one extreme, the codes for all pipe assemblies that were to be produced in the shop during a large time window would be scanned to identify identical setup requirements, and these would be bent together as a batch. At the other extreme, all assemblies would be routed through the shop so that they were completed just in time for installation, regardless of setup changes. While the optimum procedure lies somewhere between these two extremes, it is undoubtedly much closer to the latter. It is really only large pipe sizes that necessitate lengthy setup times, yet Table 7.8 shows that large pipe bending is not all that common.

If we assume that the pipe shop fabrication time for an FFG is roughly one year, then there would be an average of about 1.4 bends over four inches in diameter in the shop each working day for each FFG in the pre-fabrication stage. In the average of 7 per week there might not be any with identical setup requirements, but use of the code would provide that information and allow a formal trade-off to be done between setup time and in-process inventory. Besides detailed pipe bending data (which could come from the code), the trade-off analysis would require detailed scheduling data and specific economic data regarding the costs to the yard associated with in-process inventory.

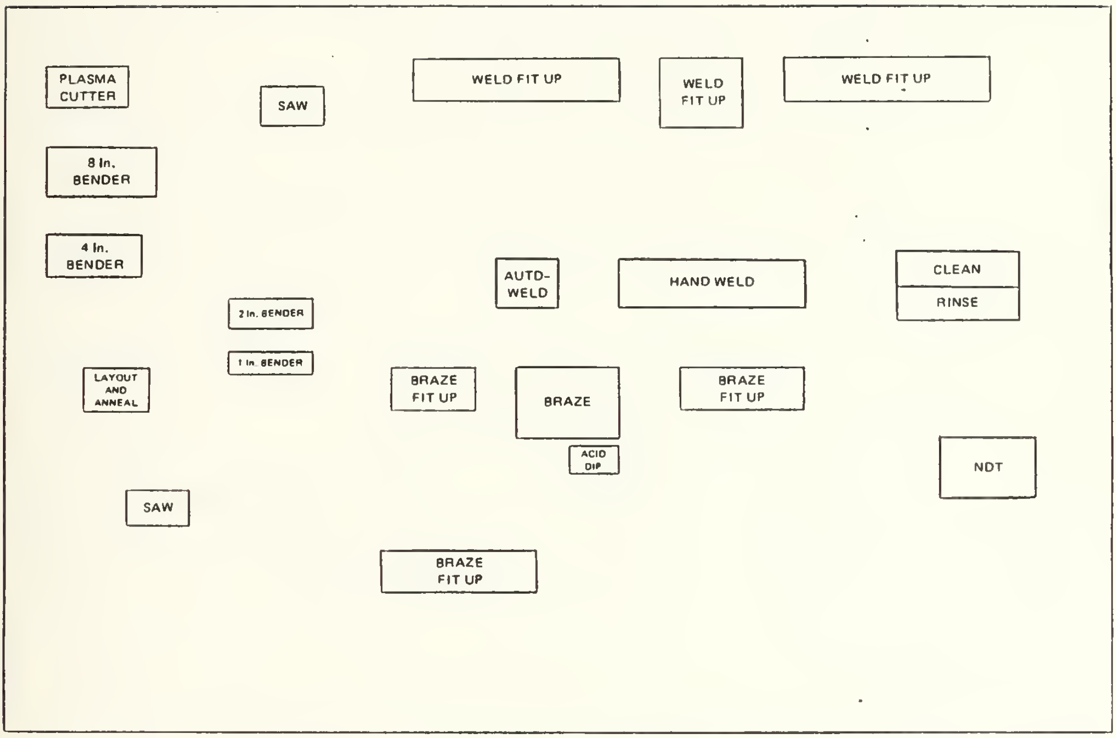


Figure 7.1. Typical shipyard pipe shop.

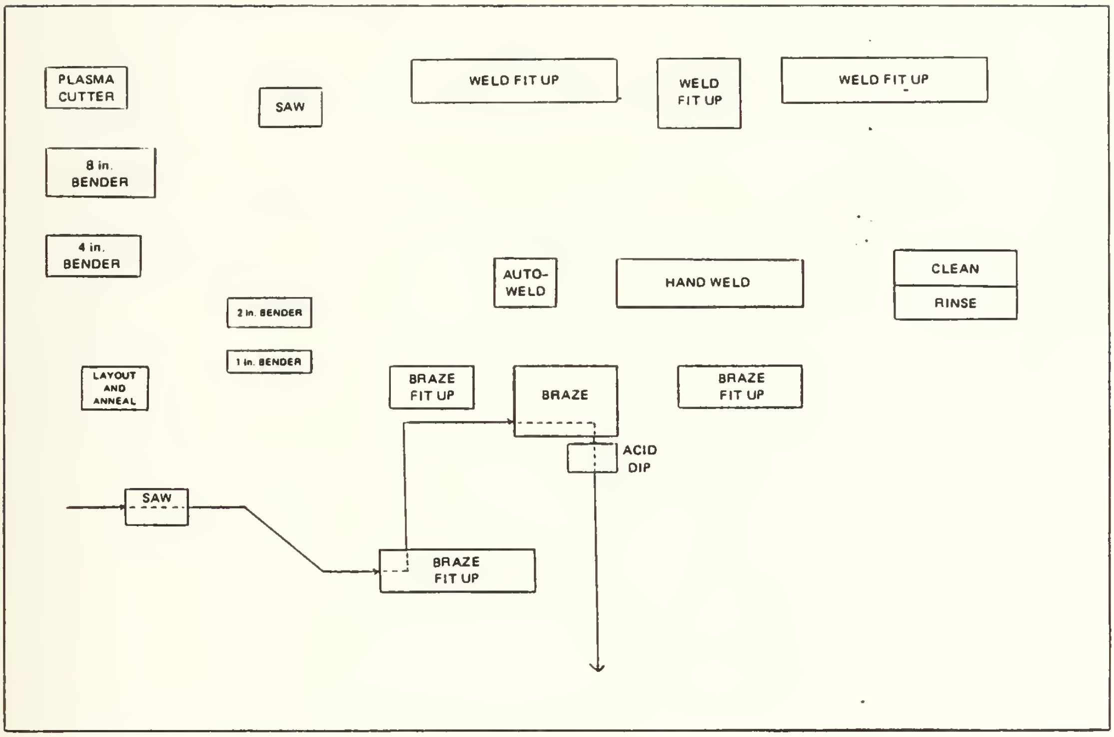


Figure 7.2. Shop routing for assembly number one.

Figure 7.2. Shop routines for currently [illegible]

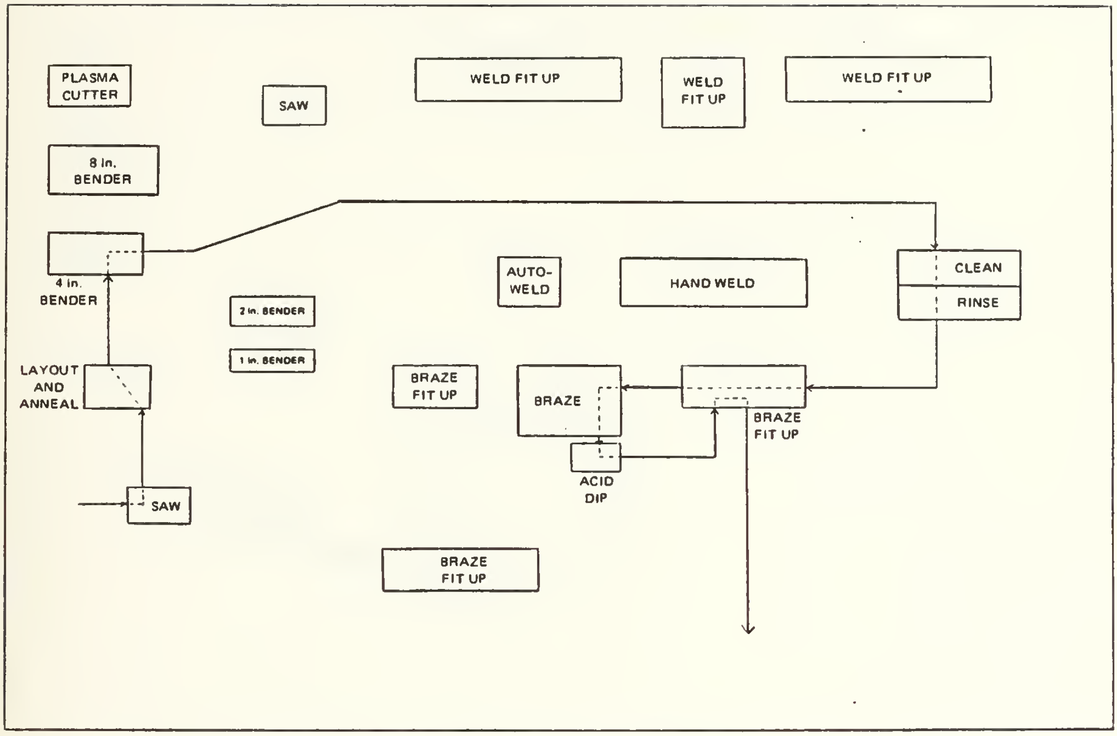


Figure 7.3. Shop routing for assembly number two.

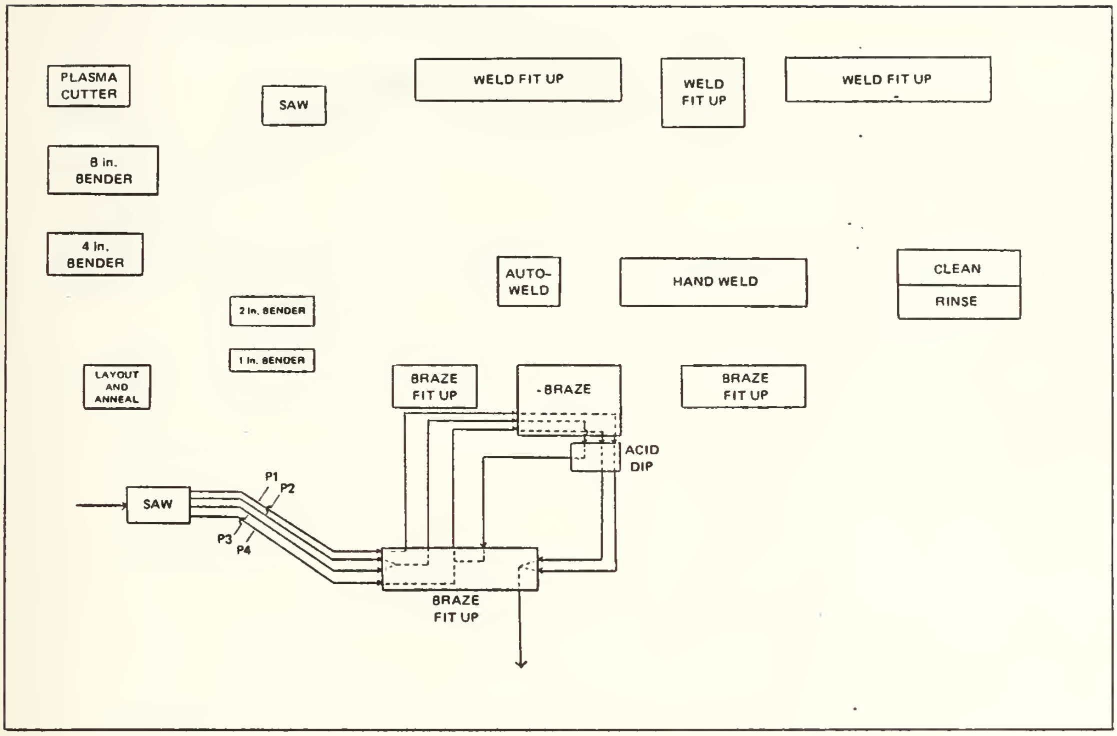


Figure 7.4. Shop routing for assembly number three.

Figure 7.4. Stop routing

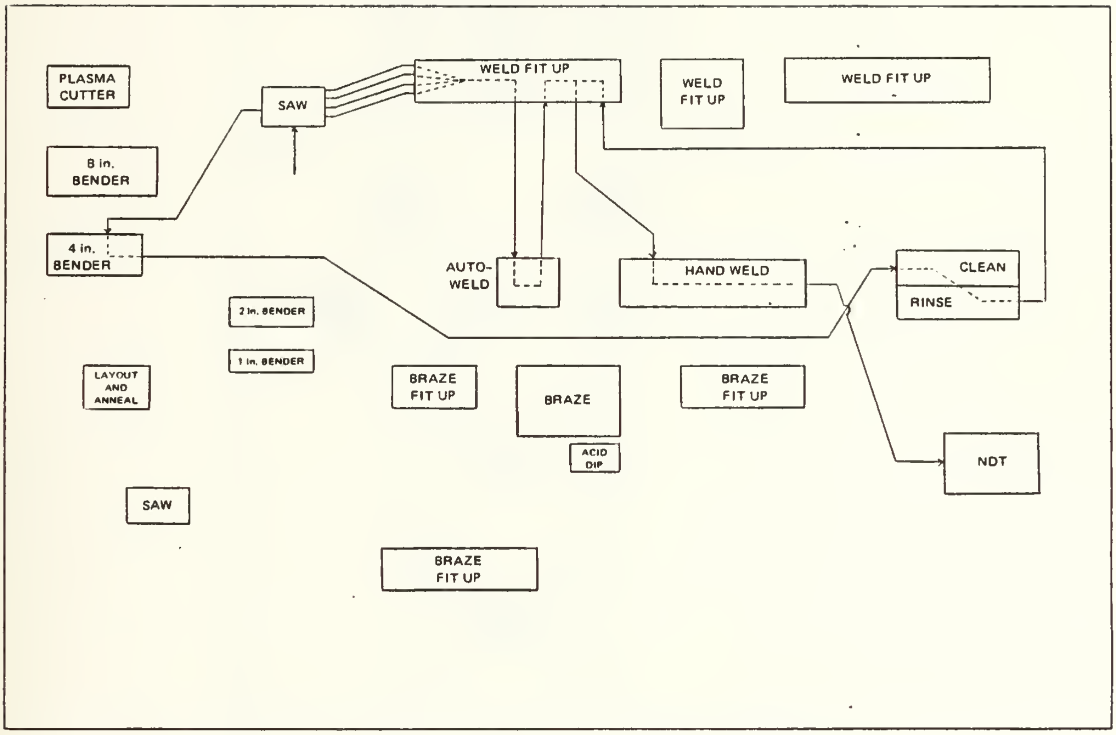


Figure 7.5. Shop routing for assembly number four.

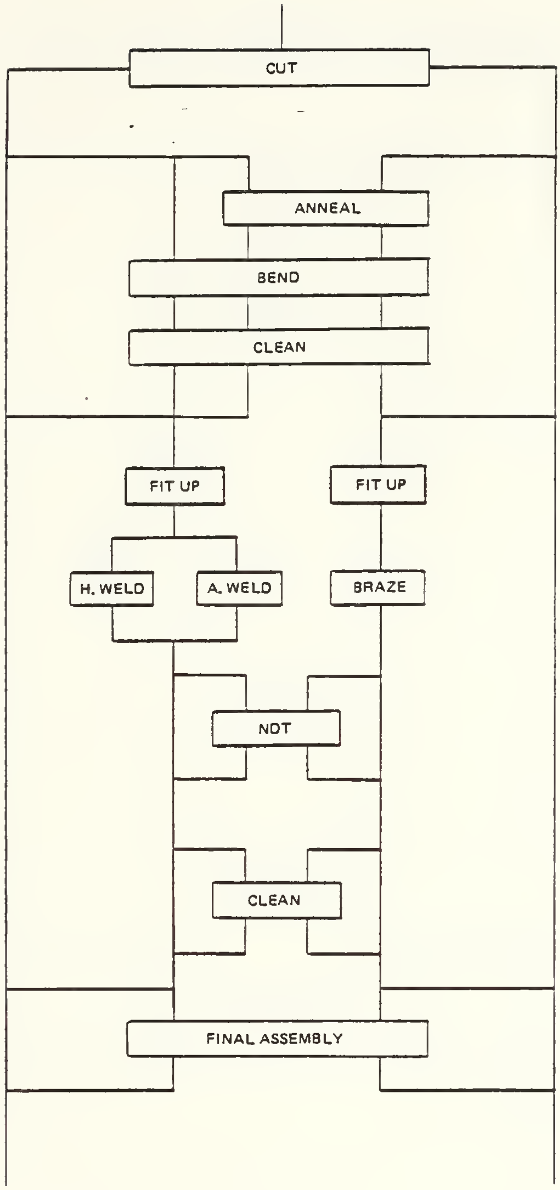


Figure 7.6. Shop routing tree.

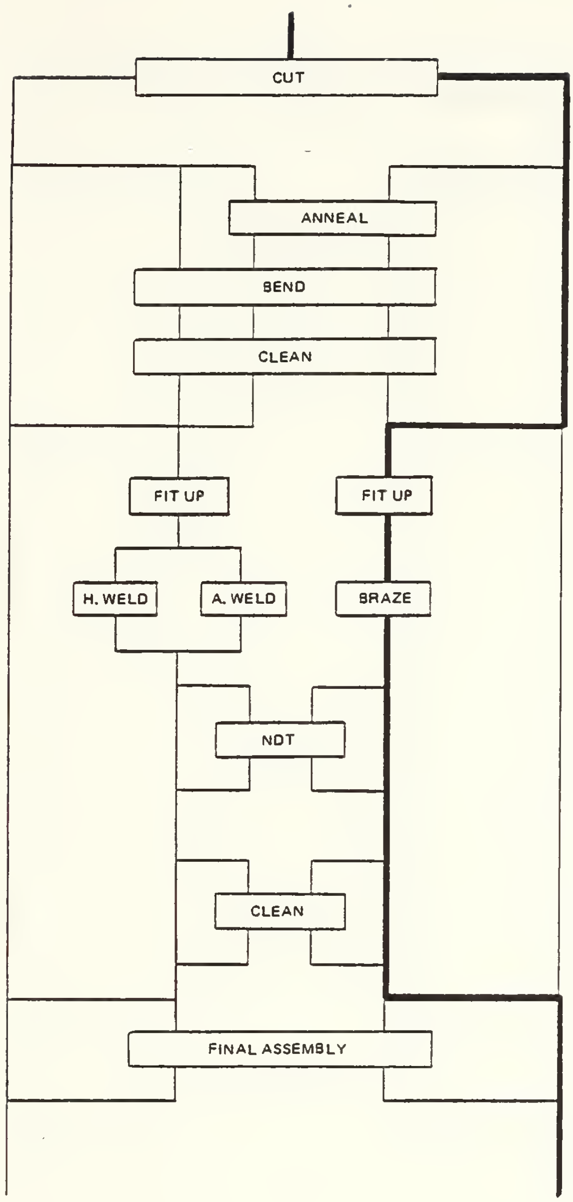


Figure 7.7. Process routing for assembly number one.

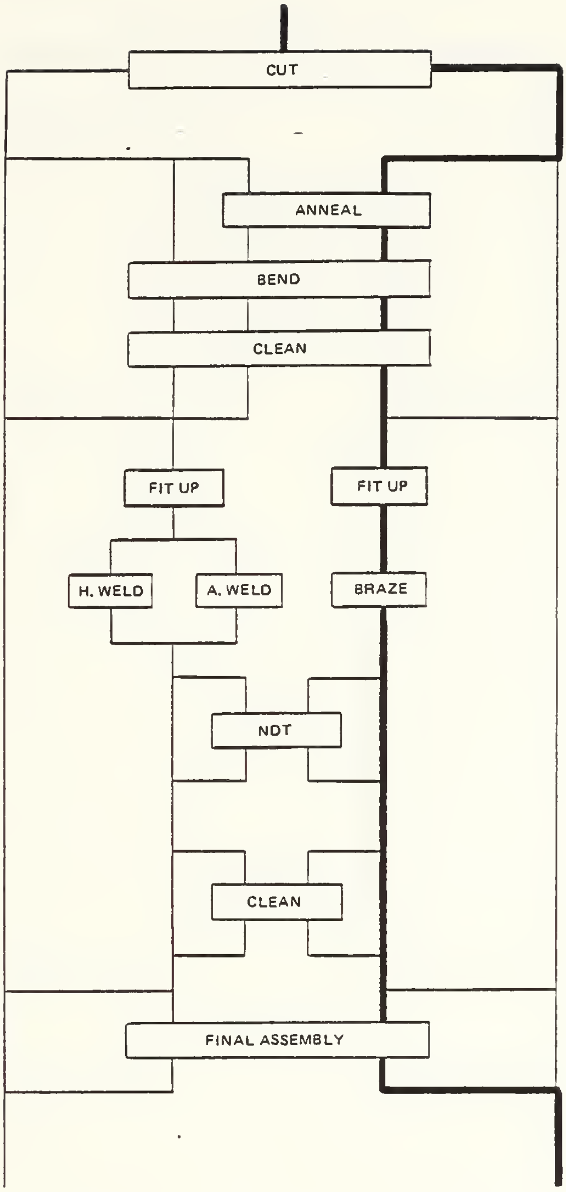


Figure 7.8. Process routing for assembly number two.

Figure 7.8. Process routing for assembly number two.

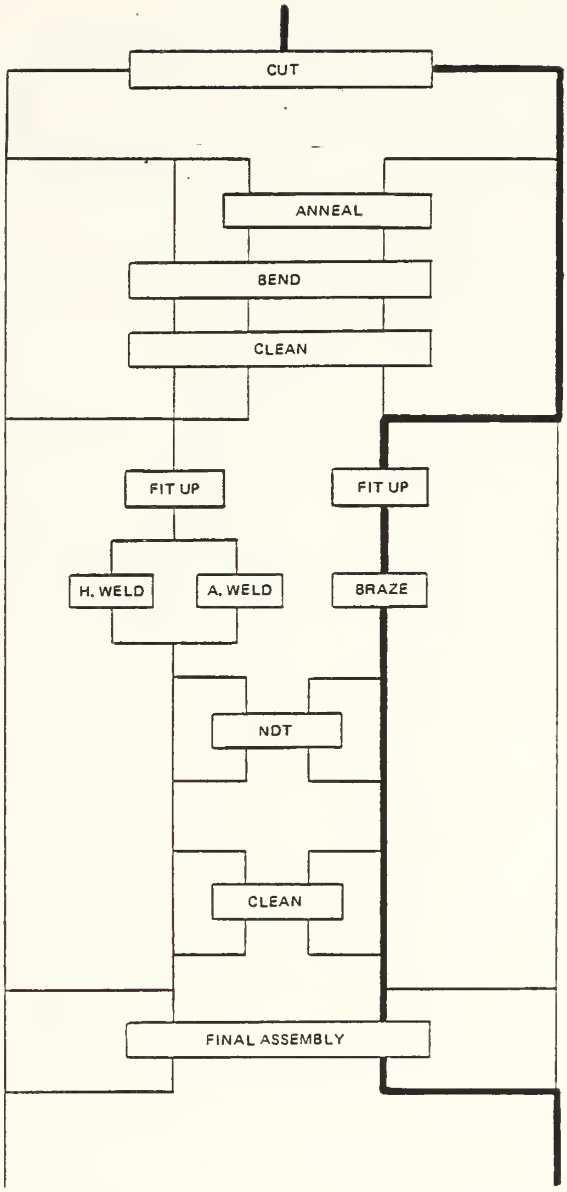


Figure 7.9. Process routing for assembly number three.

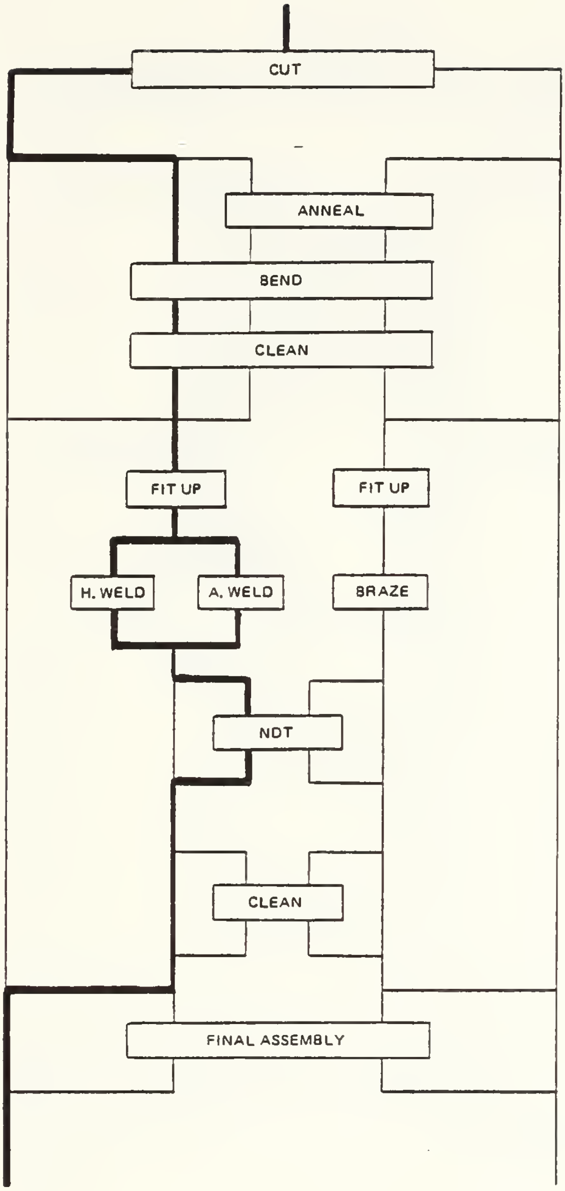


Figure 7.10. Process routing for assembly number four.

Figure 7.10. [illegible]

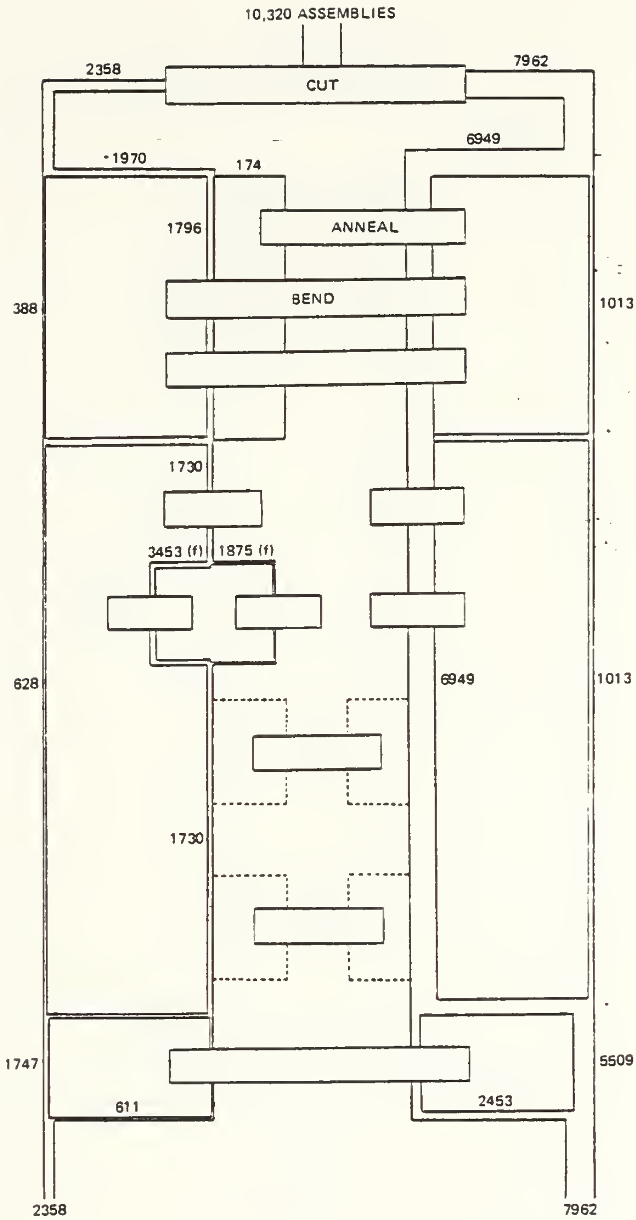


Figure 7.11. Routing tree loaded with all FFG-7 piping assemblies.

Numbers indicate number of assemblies going through each process, except for welding, where the numbers followed by an (f) indicate number of fittings. It is merely coincidence that the same number of Cu/CuNi assemblies go through bending and brazing. They are not necessarily the same assemblies.

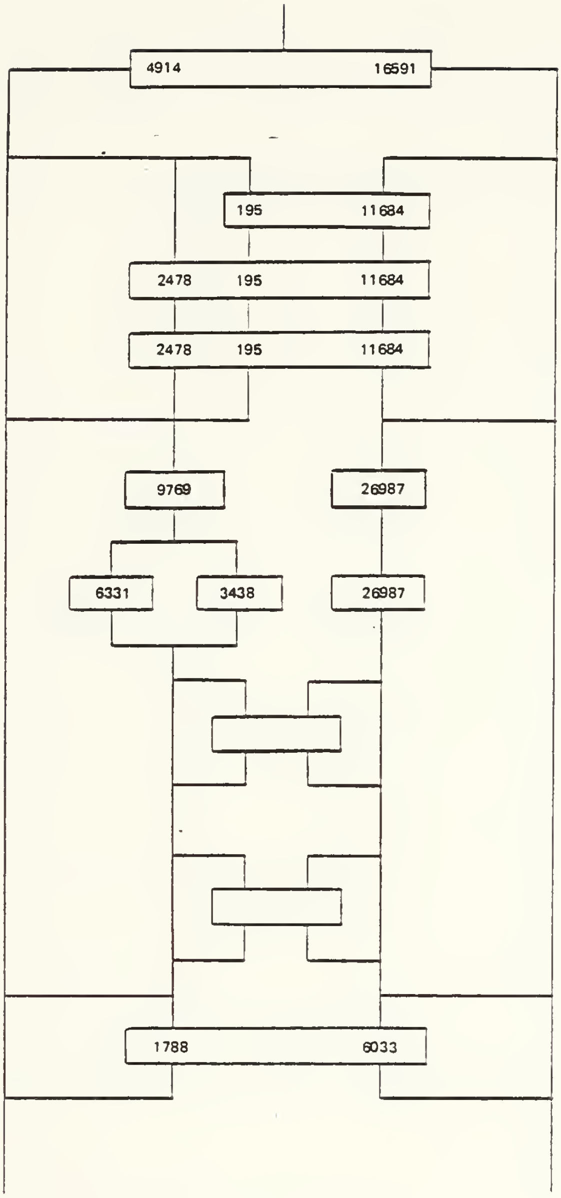


Figure 7.12. Routing tree loaded by the number of process applications for all FFG-7 piping assemblies.

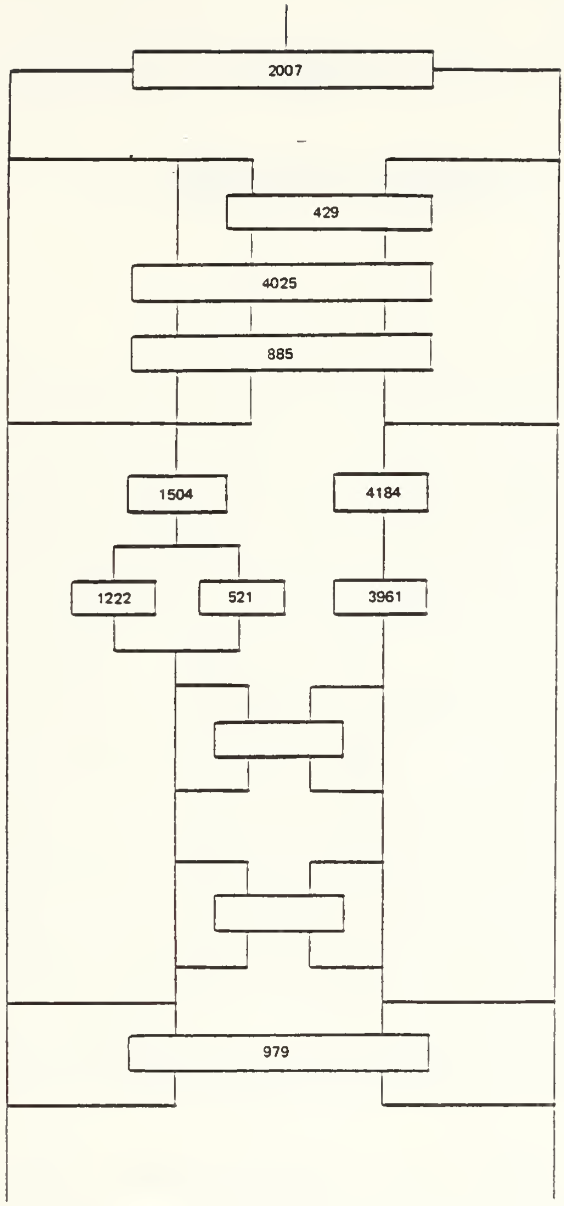


Figure 7.13. Routing tree loaded by labor man-hours for all FFG piping assemblies.

CHAPTER 8

SUMMARY AND CONCLUSION

The application of modern shipbuilding techniques in the United States is having a dramatic impact on shipyard productivity. The principles involved are not new; in fact, they were used extensively in this country during WWII. While the design simplification and quantity production that characterized WWII shipbuilding might never be duplicated, the practices of standardization and prefabrication are being utilized with increasing success. Prefabrication is applied today under the label of zone construction and outfitting. Standardization of parts and assemblies used repetitively throughout a ship is achieving the benefits of quantity production, even though we still produce very few ships.

Group technology can serve as the language of modern industrial engineering techniques. It assists standardization by identifying important product similarities, either from a design or a manufacturing point of view. Most of the shipbuilding applications thus far have been in the area of structural assemblies. It would appear, however, that pipe assemblies are another area in which GT application could be very beneficial.

The nine-digit code developed in this thesis identifies the important manufacturing attributes of shipboard pipe assemblies. It could serve as the basis for work content estimating, workload balancing, and setup time reduction. It also has limited usefulness in generative process planning. Practical use of the code, however, will require better

statistical data on pipe assemblies and labor requirements. Implementation of the code, in and of itself, would satisfy the pipe assembly data requirement as all the assemblies become coded. Labor requirements should be the topic of further investigations.

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APPENDIX A

PIPE ASSEMBLY DETAILED DRAWINGS

BATH IRON WORKS
BATH, ME.

PIPE DETA

DWG. NO. 370 598 840

CHECKED

APPROVED

SHEET NO. 12 OF

SYSTEM FIREMAIN ... 100

PIPE DETAIL NO. 1-1

PIPE ID ARR ID.	PIPE + SUFF	O.D.	THK	LENG	MTRL	SPEC CAT	UNIT NO.	REMARKS
P3"	4J	3.500	.095	3'-0"	TUBE CuNi 70/10	10043 -123	1010	F51-52 PORT SHT C

FTG. NO.	DESCRIPTION	M/L SHEET	QTY.	SYM. NO.
F12	3" SILB 90° ELL		1	1440-04

DIAGRAM

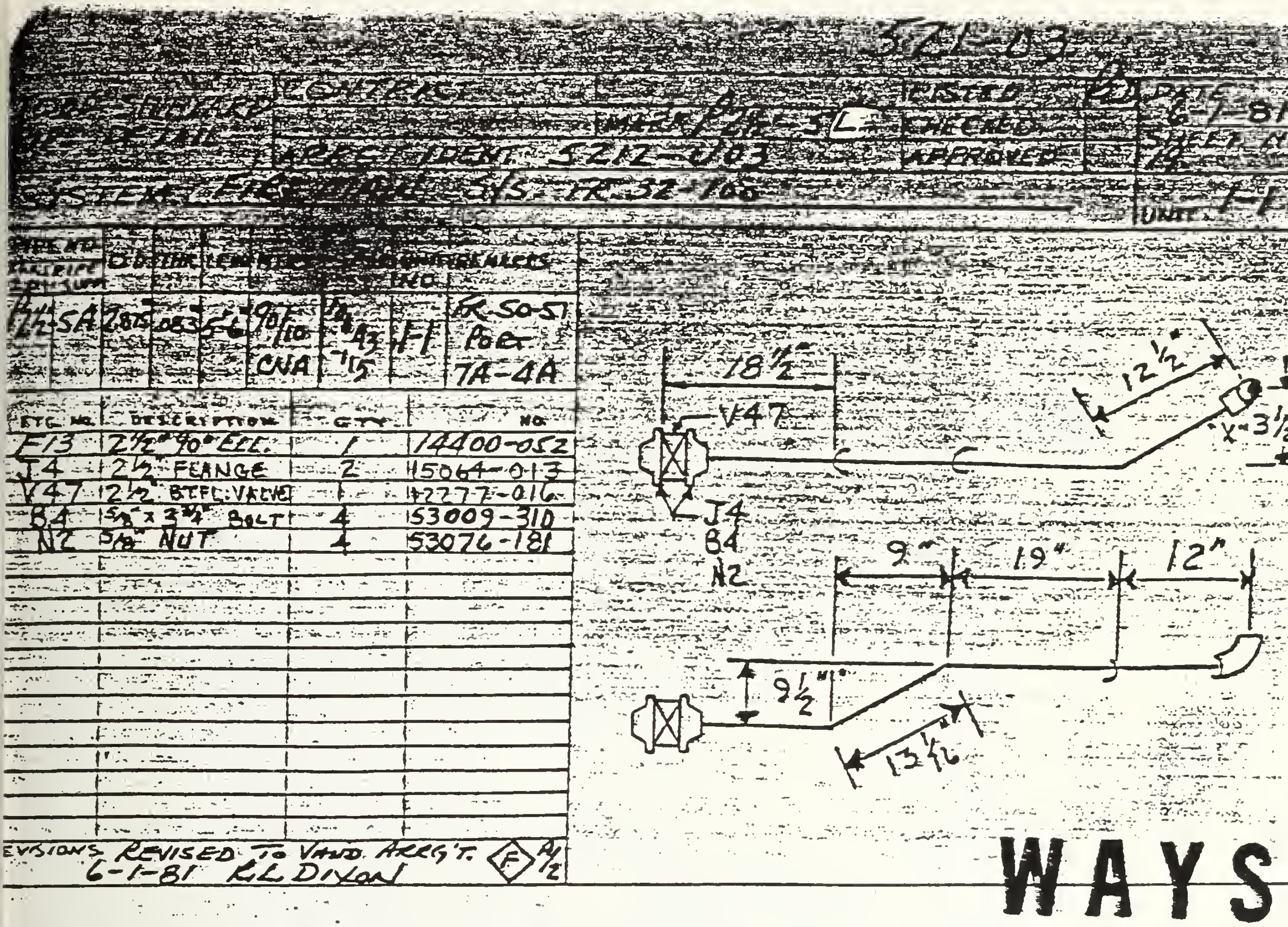
MARK P3"-4J

CUT TO SUIT

REVISIONS REVISED TO VALID ARRANGEMENT-'M' JM 12-15-77 | REVISED AS PER H.M.R. 221.2 R.D.B. 11-16-79 E

WAYS

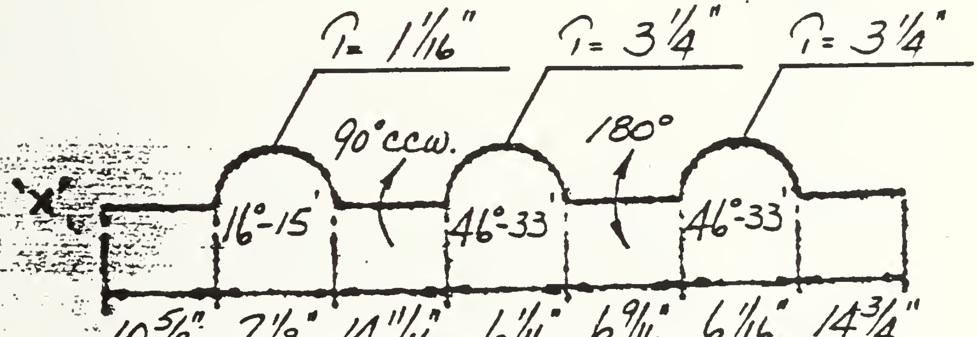
Assembly 1



TR= 12.50"
∡ = 16.2602°
∡ = 16°-15'

TR= 13.0863"
∡ = 46.5482°
∡ = 46°-33'

Rad. = 7½"
T.L. = 5'-0 7/8"



Assembly 2

PIPE DETAIL

CONTRACT		LISTED	FEB 22 1979
DWG. NO.		CHECKED	SHEET NO. 10 OF
UNIT IDENT.		APPROVED	

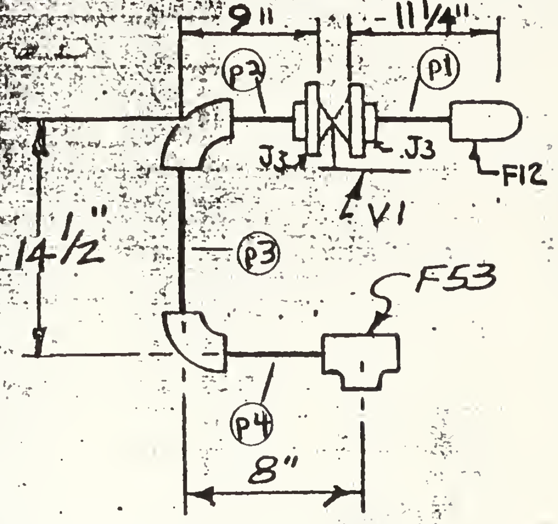
SYSTEM [illegible] FM 32-100 — PIPE DETAIL No. 1-1

PIPE NO. ARR. ID.	PIPE + SUFF.	O.D.	THK.	LENG.	MTRL.	CAT	UNIT NO.	REMARKS
P3"-4G		3.500	.095	3'-6"	TUBE CHA 70-30	10043-123	010	F53-55 STBD SHT 3

FTG. ID.	DESCRIPTION	M/L SHEET	QTY.	SYM. NO.
F12	3" SILB 90° ELL		3	14400-061
F53	3" SILB TEE		1	14410-066
V1	3" BTR FLY VLV		1	12277-024
J3	3" 200# SILB FLG		2	15064-021
B3	5/8" x 4" BOLT ZINC	PLTD	4	53009-231
N2	5/8" NUT "	"	4	53016-181

DIAGRAM

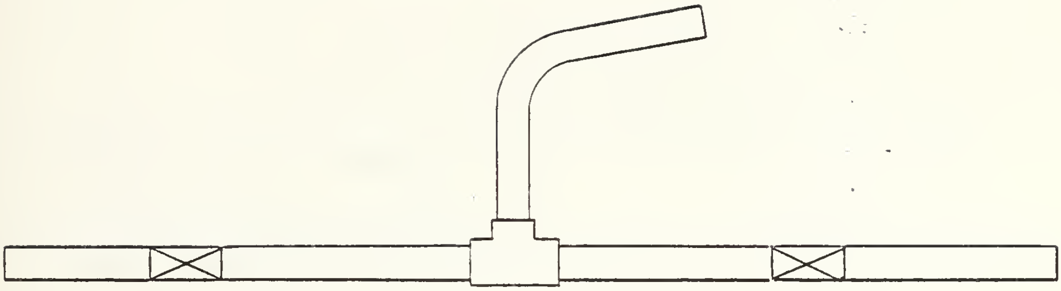
MARK P3"-4G



REVISIONS REVISED TO VALID ARRANGEMENT "M" Jm 12-15-77 | REVISED AS PER H.M.R. 221-2 R.D.B. 11-15-79 | E

WAYS

Assembly 3



Assembly 4. 4" ips steel assembly.

APPENDIX B

LIST OF SHIPYARDS VISITED

(1) Electric Boat, Quonset Point Facility, Quonset Point, RI.

(2) Bath Iron Works, Bath ME.

(3) Todd Shipyards, San Pedro, CA.

(4) Quincy Shipyards, Quincy, MA.

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(20) Ibid., p. 5.

(21) Ibid., p. 641.

(22) Ibid., pp. 35-36.

(23) Ibid., p. 51.

(24) Ibid., pp. 35, 59, 142.

(25) Ibid., p. 83.

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(27) Ibid., p. 72.

(28) Ibid., p. 94.

(29) Ibid., pp. 231.

(30) Ibid., pp. 208-209.

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